SCIENCE in HISTORY

J D BERNAL

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SCIENCE IN HISTORY

by J. D. Bernal

One of the troubles of our times is that science produces so few innovators and soaring creative minds, like J. D. Bernal's, which can at the same time relate their science, and indeed all science, to man's social and political life and history. The alienation of science in the modern world where average men and women have come to feel that science is a kind of thing apart, a never-never land of infinite complication which somehow controls one's destiny yet is uncontrollable—this alienation is partially, at least, the result of scientists having become so chained by the tyranny of their specialties and the conformity of their social outlooks that they cannot relate the grand sweep of man's mastery of nature to man's social needs. The need for a book like *Science In History*, which tells the history of science from the viewpoint of a thinker with a *scientific view of history itself* has been enormous, and never greater than in this explosive age of vast achievement unmatched in the history of man.

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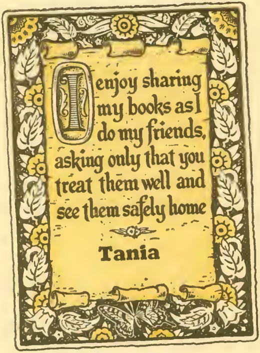

SCIENCE IN HISTORY

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Science in History

J. D. Bernal

VOLUME ONE

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J. D. B.

NOTE

In the first edition of this book I avoided the use of footnotes throughout the text. A few notes have been added to this edition and are marked with an asterisk (*) or a dagger (†) (if there is more than one footnote on a page). The notes have been collected at the end of the book and are referred to by their page numbers.

The reference numbers in the text relate to the bibliography, which is also at the end of the book. The bibliography has eight parts: Parts I–VII correspond to those of the book; Part VIII contains the new books and references added for this edition. Parts I–VI of the bibliography are divided into sections within which books and articles are listed alphabetically by author.

Part I of the bibliography is divided into three sections. The first contains books which cover the whole work, including general histories of science. The second section contains histories of particular sciences and the books relevant to Part I. The third section lists periodicals to which reference has been made throughout the book.

Parts II, III, IV, and V of the bibliography are each divided into two sections. The first section in each case contains the more important books relevant to the part, and the second the remainder of the books.

In Part VI of the bibliography the first section contains books covering the introduction and Chapter 10, the physical sciences; the second section, Chapter 11, the biological sciences; and the third, Chapters 12 and 13, the social sciences.

Parts VII and VIII of the bibliography are not subdivided.

The system of reference is as follows: the first number refers to the part of the bibliography; the second to the number of the book in that part; and the third, when given, to the page in the book referred to. Thus 2.3.56 refers to page 56 of the item numbered 3 in the bibliography for Part II, i.e. Farrington's *Science in Antiquity*.

It should be noted that books appear only once in the bibliography—in the most appropriate part. Thus it is possible for a reference in Part II of the book to refer to a book listed in Part V of the bibliography.

PREFACE

In 1948 I was asked to deliver the Charles Beard Lectures at Ruskin College, Oxford. The subject I chose was "Science in Social History." It was one that had interested me for many years and there seemed no difficulty in presenting it to an intelligent and unspecialized audience. When I came to give the lectures, and still more when I undertook to present them in book form, I began to realize that I had opened a subject that required far more study and hard thinking than I had given it up till then. It was, however, one far too fascinating to put down, and I decided to persevere in it. The first result of that intention is this book, one which I hoped to prepare in three weeks but which has already taken me twice that number of years. It is only now that I am beginning to understand what are the problems of the place of science in history.

Scientists in the past were able to neglect all but their immediate predecessors' work and even to reject the traditions of the past as more likely to block than assist progress. Now, however, the troubles of the times, together with the inescapable connection between them and the advance of science, have focused attention on the historical aspect of science. To find how to overcome the difficulties that face us and to release the new forces of science for welfare rather than destruction, it is necessary to examine anew how the present situation came about.

In the last thirty years, largely owing to the impact of Marxist thought, the idea has grown that not only the means used by natural scientists in their researches but also the very guiding ideas of their theoretical approach are conditioned by the events and pressures of society. This idea has been violently opposed and as energetically supported; but in the controversy the earlier view of the direct impact of science on society has become overshadowed. It was my purpose to emphasize once more to what extent the advance of natural science has helped to determine that of society itself; not only in the economic changes brought about by the application of scientific discoveries, but also by the effect on the general frame of thought of the impact of new scientific theories.

I soon found, however, that this involved far more than drawing up a catalogue of inventions and hypotheses and illustrating by examples how these affected economic and political developments. This had been done often enough already. If anything new and significant was to be hoped for nothing less would be adequate than a complete re-examination of the reciprocal relations of science and society. It would be as one-sided to assess the effects of science on society as of society on science.

Nor would it be enough to confine the inquiry to recent times. This might have sufficed if all that was sought was the effects of the material changes in the pattern of life brought about in the Industrial Revolution and at an accelerated pace ever since. But if in addition it was necessary to seek to discover how the advance of science had altered the whole frame of human thought, it would also be necessary to go back through the great controversies of the Renaissance about the nature of the heavens, and then still farther back to the Ancients, without whose theories the controversies would have no meaning.

There was nothing for it but to attempt to trace the whole story from the very origins of human society. This involved a parallel study of all social and economic history in relation to the history of science, a task well beyond the scope of any individual, even of those who have devoted their whole lives to historical studies. For a busy scientist untrained in the techniques of historical research it would be sheer presumption to attempt a serious full-scale analysis and presentation of this aspect of history. Yet there seemed some excuse for making a first attempt to sketch out the field, if only to stimulate, through its omissions and errors, others more leisured and better qualified to produce a more authoritative picture. Moreover, there was a compensating advantage in the position of a working scientist who has lived long enough to have followed through, and even participated in, the scientific movements of critical periods, both of science and of social change. I have indeed been exceptionally fortunate in having first-hand experience in the carrying out and organization of scientific work, and in seeing it called for and used for practical purposes both in peace and in war.

It is in the light of that experience that I have attempted to evaluate the conditions and attitudes that have prevailed inside and outside science in other times. No attempt is made here

to present a chronologically uniform picture. The present century has witnessed such an immense upsurge of science and has seen that science used so rapidly and to such effect—to cite no other examples than penicillin and the atom bomb—that consideration of the development of twentieth-century science has required a good half of the book. Here the scientist of the day is in as good a position as the historian, and every reader can criticize from his own experience.

Science throughout is taken in a very broad sense and nowhere do I attempt to cramp it into a definition. Indeed, science has so changed its nature over the whole range of human history that no definition could be made to fit. Although I have aimed at including everything called science, the centre of interest of the book lies in natural science and technology because, for reasons that will be discussed, the sciences of society were at first embodied in tradition and ritual and only took shape under the influence and on the model of the natural sciences. The theme which constantly recurs is the complex interaction between techniques, science, and philosophy. Science stands as a middle term between the established and transmitted practice of men who work for their living, and the pattern of ideas and traditions which assure the continuity of society and the rights and privileges of the classes that make it up.

Science, in one aspect, is ordered technique; in another, it is rationalized mythology. Because it started as a hardly distinguishable aspect of the mystery of the craftsman and the lore of the priest, which remained separate over most of recorded history, science was long in establishing any independent existence in society. Even when it did find its own specific adepts in medicine, astrology, and alchemy, these formed for many ages a small group parasitic on wealthy princes, clerics, and merchants. It is only in the last three centuries that science has become traditionally established as a profession in its own right, with its specific education, literature, and fellowship. Now, in our own time, we are witnessing a beginning of a return to the earlier state of humanity through a general pervasion of science into all forms of practical activity and thought, bringing together once more the scientist, the worker, and the administrator.

The progress of science has been anything but uniform in time and place. Periods of rapid advance have alternated

with longer periods of stagnation and even of decay. In the course of time the centres of scientific activity have been continually displaced, usually following rather than leading the migration of the centres of commercial and industrial activity. Babylonia, Egypt, and India have all been the foci of ancient science. Greece became their common heir, and there the rational basis for science as we know it was first worked out. That forward movement of human thought came to an end even before the final decay of the classical city States. There was little place for science in Rome and none in the barbarian kingdoms of western Europe. The heritage of Greece returned to the East from which it had come. In Syria, Persia, and India, even in far-away China, new breaths of science stirred and came together in a brilliant synthesis under the banner of Islam. It was from this source that science and techniques entered medieval Europe. There they underwent a development which, though slow at first, was to give rise to the great outburst of creative activity which resulted in modern science.

An unbroken and active tradition links us with the revolutionary science of the Renaissance, though we can distinguish in its development four major periods of advance. The first, centred in Italy, produced the renewal of mechanics, anatomy, and astronomy with Leonardo, Vesalius, and Copernicus, destroying the authority of the Ancients in their central doctrines of man and the world. The second, spreading now to the Low Countries, France, and Britain, beginning with Bacon, Galileo, and Descartes, and ending in Newton, hammered out a new mathematical–mechanical model of the world. After an interval, the third transformation, centred in industrial Britain and revolutionary Paris, opened to science areas of experience, such as that of electricity, untouched by the Greeks. It was then that science could help in a decisive way with power, machinery, and chemicals, to transform production and transport. The fourth and greatest of all in extent and effect, if not in intrinsic intellectual performance, is the scientific revolution of our own time. We are witnessing the beginning of a world science, transforming old and creating new industries, permeating every aspect of human life. It is now also, during this period of transition, that we find science directly involved in the violent and terrible drama of wars and social revolution.

It is by now apparent that each of these great periods of science corresponds to one of social and economic change.

Greek science reflects the rise and decline of the money-dominated, slave-owning iron age society. The long interval of the Middle Ages marked the growth and instability of feudal subsistence economy with little use for science. It was not until the bonds of feudal order were broken by the rise of the bourgeoisie that science could advance. Capitalism and modern science were born in the same movement. The phases of the evolution of modern science mark the successive crises of capitalist economy. The first two periods coincide with its early battles and its first success in establishing itself as the dominant economy in Holland and Britain. The third ushered in the factory system and seemed to forecast the triumph of a progressive capitalism allied to science. By the time the last had come capitalism was already overgrown and over-reaching itself, and the new form of socialism was visibly struggling to replace it and to take over, in order to use in its own way the now proved forces of science.

To write this, however, is only to begin to state the problem. These rough equations between social and scientific development give rise to one central question. How in detail does a social transformation affect science? What gave the science of ancient Athens, of Renaissance Florence, of eighteenth-century Birmingham and Glasgow, its particular drive and novelty? How, conversely, did the achievements of the scientists of those times and places affect the industry, the commerce, the politics, and religion of their contemporaries? How much of that effect was permanent and how much a passing fashion? These are questions which I have examined and attempted to answer.

I have tried, in doing this, to take into account as many as I could of the relevant factors. I have tried to determine and describe the technical possibilities and limitations of each period, the degree of economic incentive for urging on and fixing securely the advances that were made. But advances are not made by impersonal forces, but by living men and women. Their lives and livelihoods, their motives, the relations with the political movements of the time, had all to be considered. It was necessary to estimate from their works and writings how far they were stimulated, or how far retarded, by the ideas they drew from old traditions or from the active controversies of their times.

At every turn this conflict between the forces tending to advance and those tending to retard science comes into prominence. We can perceive the positive progressive forces

breaking through at the beginning of each critical advance, and the regressive forces of pedantry and obscurantism reasserting themselves at its close. Yet in each case the circumstances are different and require a separate examination.

It would be absurd to expect to find any simple explanations of the critical phases of the development of science. Nevertheless merely to bring out the connections between social, technical, and scientific factors should be enough to lead to further study and to a deeper, even if unformulated understanding. I know myself that this returning to the past has inevitably coloured my comprehension of the present and my ideas of the future path of science. True, in science, more perhaps than in any other field of human enterprise, progress is possible, and has indeed largely occurred, without any knowledge of history; but that knowledge is bound to affect the future direction and course of science and, if the lessons of the past have been well read, progress will be quicker and surer.

This book represents a first attempt to put down in order some of these lessons of the past. It is not, nor is it intended to be, another history of science, though it must needs set out again much of that history and refer to more. Its aim is to bring out the influence of science upon other aspects of history, whether direct or indirect, through its effect on economic changes, or through its influence on the ideas of the ruling classes of the day or of those who are striving to supplant them. But, as will be seen, these influences are rarely clear-cut, nor are they usually one-way influences. Often enough the ideas which the statesmen and divines think they have taken from the latest phase of scientific thought are just the ideas of their class and time reflected in the minds of scientists subjected to the same social influences. Certainly much of the influence of Newton and Darwin in Britain was of that character, but this did not prevent them from being revolutionary when they were presented elsewhere against a different social background.

The more I followed up the social historical interactions of science the closer knit they appeared. I began to see something of the size and intricacy of the task I had attempted and the absolute impossibility of presenting at the same time a fully convincing and intelligible picture. If I did not put in enough I should be accused of imposing ready-made solutions; if I put in too much the reader would lose the clue in a mass of detail. I have sought the best compromise I could find, but

what I have managed to produce is admittedly less well documented and less closely argued than the finished work I originally planned. It will succeed in the measure that the reader can follow the course of the history traced out. Rather than assenting to any particular conclusion of mine, I would wish him to look at history in a new way, to make his own discoveries and frame his own theories.

Length and time imposed severe limitations. I must write a book, not an encyclopædia, and I must bring it to an end in a finite number of years. These, and the fact that I have never been able to find any continuous stretch of time for writing but have had to take it up and drop it at odd intervals, are responsible for some of its defects, of which no one can be more aware than I. I know that the history is full of omissions and errors in detail that could have been put right had I had the time and the scholarship to discover and deal with them. I hope vigilant readers will point them out and not dismiss the whole work because in some field in which they have a special competence they have found me straying. What I must hope is that these errors as to established facts, as well as other errors which stem from gaps in the record, will not radically affect the validity of the theses I am sustaining. No scientist can be, nor can he seriously want to be, guaranteed against reversals of judgment in the long run. All he can hope for, as I do, is to establish enough valid and significant connections between facts, even if they are later overthrown, to serve as a basis for finding new facts and new connections.

The plan of the book was originally determined by that of the lectures from which it grew, but each lecture became first a chapter and has then swollen into a part containing a number of chapters. The introductory chapter (Part I, Chapter 1) is one in which the major problems are stated, and there is some discussion in general on the nature and method of science and on its place in society. Because of its somewhat abstract character non-scientists might be advised to leave it until after reading the historical and descriptive portions. Those contained in Parts II, III, IV, and V, making up the first half of the book, deal with the whole range of history from the dawn of human society to the eve of the twentieth century. Part II, Chapters 2, 3, and 4, deals with the emergence of science from its forerunners in technique and social custom to its full formulation in the hands of the Greeks. In Part III, Chapters 5 and

6 deal with the recovery and slow growth of a science and technology, through Islam and Christendom, to the end of the Middle Ages.

Part IV, which contains only Chapter 7, deals with the birth of modern science in the great revolutionary epoch of the Renaissance. It ends in the seventeenth century with a renewed science closely linked with a young and assertive capitalism. Part V, Chapters 8 and 9, is mainly the record of the spread of an established science and its share in the transformation of industry in an era of capitalist domination up to the illusory golden age of the end of the nineteenth century.

Part VI is nearly all devoted to the twentieth century and largely to contemporary science and politics. It is divided not by time, but by subject. Chapter 10 deals with the physical sciences, with the growth of the electrical and chemical industries, and with the culminating achievement, for ill or good, of the hydrogen bomb. Chapter 11 deals with the biological sciences and their impact on agriculture, medicine, and warfare. Chapters 12 and 13 enter the disputed field of the social sciences, which for continuity needs to be traced back beyond the confines of the century. In all the historic chapters, 2–13, the plan is first to present a picture of social and scientific development of each successive period, and then to bring out the relations between them. The last Part, VII, Chapter 14, attempts to summarize and draw conclusions, with an eye to the future, from the whole of history.

The scope is evidently comprehensive, but to obtain the results aimed at this is necessary. A partial account would miss the point of presenting the total picture, for it would inevitably fail to question what is taken for granted in what is omitted. Even to leave out remote and uncertain origins would not do, for, as I hope to show, much of what is obscure and difficult in the science of our times and in its social context depends on attitudes and institutions passed down from those times.

No more need be written here. The book itself is the only test of whether I have succeeded in what I set out to do and to what degree it was worth doing.

London,
April, 1954 J. D. B.

PREFACE TO THE SECOND EDITION

A SECOND edition of what is primarily an historical work brought out within three years of the first would normally call for little comment by the author. But, because this book is also largely concerned with the contemporary world, the changes in these three years have inevitably called for considerable additions and alterations. Nor does the science of history itself stay still; new facts and new interpretations have appeared in the interval and these, together with the pertinent remarks of my critics, have to be taken into account. In order not to lengthen the book unduly I have cut out some less important material to be able to include later developments and have accommodated some more detailed information in a set of notes placed at the end of the volume.

Since writing the first edition the trend in international affairs has in the main been towards a relaxation of tension. This trend, I still feel, is so deep-seated and corresponds so much to popular needs that it is likely to survive the strains of the crises of the autumn of 1956. Accordingly, in rewriting the relevant parts of the first edition, which were written during the most acute period of the Cold War, I have tried to bring out the constructive possibilities of science in the hope that the world may settle down to develop its economy and science in peace.

On account of the great changes that have occurred since the death of Stalin I have largely rewritten the section dealing with the Soviet Union and neighbouring countries, correcting as far as information is available errors in the first edition. I have also added something on the remarkable growth of former colonial countries in Asia and Africa and on the weight of their influence as a group of neutral powers.

Despite all these peaceful developments, the threat of war has by no means vanished. No agreement has been reached on disarmament or on the prohibition of nuclear weapons. From what has recently emerged as to the scale of destruction which a hydrogen bomb war would produce it is certain that if we do not have peace there will be little left of science, civilization,

or humanity on this earth. This new knowledge has necessitated rewriting the section on *War and Science*.

In contrast to these most alarming developments, the positive prospects of science are coming much more clearly into view. Atomic energy for peaceful uses is an accomplished fact, and it is already evident that in its present fission form, or as thermonuclear energy, it will provide—if there is no war—before another generation passes, power and wealth such as man has never enjoyed before. To use this power and to abolish the monotonous work which holds humanity down in field and mine, factory and office, we now have automation and electronic computors.

These material achievements are only the expression of the power of research to deal with problems, fascinating in themselves and of immediate use to man. In physics and in biology enormous advances have been made in the last three years, and we seem to be on the eve of new, great, illuminating theories on the structure of matter and of life.

It is becoming apparent that from now on a much greater effort must be devoted to research and teaching in science and technology, and that the advantages of the new age can be won and enjoyed only by a new fully educated population unlimited by class or race. Science is too important and too dangerous to be left to the few.

Such great changes cannot possibly occur without transformations in political and economic institutions. Some conflict is inevitable, but it can no longer be allowed to result in war. The problems of a world without war have still to be faced. Today to maintain the present inequalities, to keep most of the world on the edge of starvation so that a relative few can enjoy a limited, illusory, and frightened prosperity, is costing an effort which if properly directed would mean within a few years far greater prosperity for all. People who have fought and cheated to get a little more for themselves in a world of scarcity must be brought to realize that a world of plenty is there for the asking.

The decisive role of science in shaping the future of the world is no longer in question. For its wise use, it will still be of value to study its history in its social context.

J. D. B.

London, November, 1956.

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PART I

THE EMERGENCE AND CHARACTER OF SCIENCE

Chapter 1
INTRODUCTION

This book is an attempt to describe and to interpret the relations between the development of science and that of other aspects of human history. Its ultimate object is to lead to an understanding of some of the major problems which arise from the impact of science on society. Civilization as we know it today would, in its material aspects, be impossible without science. In its intellectual and moral aspects science has been as deeply concerned. The spread of scientific ideas has been a decisive factor in remoulding the whole pattern of human thought. Especially do we find in the conflicts and aspirations of our time a continual and growing involvement of science. Men live in fear of destruction by the atom bomb or biological weapons; in hope of living better lives through the application of science in agriculture and medicine. The two camps into which the world is now divided exemplify different objectives in the use of science. The urgency to reconcile them is also in part due to the catastrophic and suicidal nature of scientific warfare.

The march of events brings before us, ever more insistently, problems about science such as: the proper use of science in society, the militarization of science, the relations of science to governments, scientific secrecy, the freedom of science, the place of science in education and general culture. How are such problems to be solved? Attempts to solve them by appeals to accepted principles or self-evident truths have led so far only

to confusion. They can give no clear answer, for instance, as to the responsibility of the scientist to the tradition of science, to humanity, or to the State. In a rapidly changing world little can be expected from ideas taken unaltered from a society that has vanished beyond recall. But this is not to say that the problems are insoluble, and in consequence to lapse into the impotent pessimism and irrationality that are so characteristic of intellectuals in capitalist countries today.[1.30] Ultimately these problems must be solved and will be answered in practice in the process of finding the way of using and developing science most harmoniously and with the best results for humanity. Already much experience has been gained in countries where science has been consciously devoted to the tasks of construction and welfare. Even in Britain and America the experience of the use of science in war and war preparation has taught scientists something of what could be done in peace.[1.2.285]

But experience by itself is not enough, and indeed it can never operate alone. Consciously or unconsciously it is bound to be guided by theories and attitudes drawn from the general fund of human culture. In so far as it is unconscious, this dependence on tradition will be blind and will lead only to the repetition of attempted solutions that changed conditions have made unworkable. In so far as it is conscious, it must involve a deeper knowledge of the whole relation of science to society, for which the first requirement is the knowledge of the history of science and of society. In science, more than in any other human institution, it is necessary to search out the past in order to understand the present and to control the future.

Such an assertion would, at least until recently, have received scant support from working scientists. In natural science, and especially in the physical sciences, the idea is firmly held that current knowledge takes the place of and supersedes all the knowledge of the past. It is admitted that future knowledge will in turn make present knowledge obsolete, but for the moment it is the best available knowledge. All useful earlier knowledge is absorbed in that of the present; what has been left out are only the mistakes of ignorance. Briefly, in the words of Henry Ford, "History is bunk."

Fortunately more and more scientists in our time are beginning to see the consequences of this attitude of neglect of history, and with it, necessarily, of any intelligent appreciation of the place of science in society. It is only this knowledge that can

prevent the scientists, for all the prestige they enjoy, being blind and helpless pawns in the great contemporary drama of the use and misuse of science. It is true that in the recent past scientists and people at large got on very nicely in the comfortable belief that the application of science led automatically to a steady improvement in human welfare. The idea is not a very old one. It was a revolutionary and dangerous speculation in the days of Roger Bacon (p. 226) and was first confidently asserted by Francis Bacon (pp. 304 f.) 300 years later. It was only the immense and progressive changes in science and manufacture that came about with the Industrial Revolution that were to make this idea of progress an assured and lasting truth—almost a platitude (p. 488)—in Victorian times. It is certainly not so now, in these grim and anxious days, when the power that science can give is seen to be more immediately capable of wiping out civilization and even life itself from the planet than of assuring an uninterrupted progress in the arts of peace. Though even here doubt has crept in and some neo-Malthusians fear that even curing disease is dangerous on an overcrowded planet (p. 680).

Whether for good or ill the importance of science today needs no emphasizing, but it does, just because of that importance, need understanding. Science is the means by which the whole of our civilization is rapidly being transformed. And science is growing; not, as in the past, steadily and imperceptibly, but rapidly, by leaps and bounds, for all to see. The fabric of our civilization has already changed enormously in our own lifetimes and is changing more and more rapidly from year to year. To understand how this is taking place it is not sufficient to know what science is doing now. It is also essential to be aware of how it came to be what it is, how it has responded in the past to the successive forms of society, and how in its turn it has served to mould them.

Some people take it for granted that, because science is affecting our lives more and more, it follows that the scientists themselves are in effective control of the mechanism of civilization and that in consequence they are immediately and largely responsible for the evils and disasters of our time. Most of those actually working in science know well enough how far this belief is from the truth. The use to which the work of the scientists is put is almost completely out of their hands. The responsibility of the scientists remains, therefore, a purely

moral one. Even that responsibility is usually evaded in the tradition of science by the exaltation of the disinterested search for truth, irrespective of any consequences that may arise from it. This convenient evasion of responsibility, as we shall see (p. 485), worked well enough as long as general social progress, largely thanks to science, seemed to be the order of the day. Then the scientist could identify himself reasonably easily with the current economic and political trends and be happy enough to be left alone to pursue his freely chosen path. But in the face of a world of increasing want, misery, and fear, and one too where science itself is more and more directly involved in the more unpleasant aspects of warfare, this attitude is beginning to break down. The moral responsibility of the scientist in the world of today is difficult to evade.

The alternative is not irresponsibility, but a more conscious and active social responsibility where, on the one hand, science can make an explicit contribution to the planning of industry, agriculture, and medicine, for ends of which the scientist can fully approve; and where, on the other hand, science can be so extended and transformed as to become an integral part of the life and work of all.

The change from a socially irresponsible to a socially responsible science is one which is only just beginning. Its nature and directives are not yet fully formulated. It is only one aspect, though a vital one, of the major social transformations from an economy motivated by individual acquisitiveness to one directed to common welfare. This is going to be one of the most momentous changes in the whole of human history, and hence it is of the utmost importance that it should be fully debated and well understood in advance, for it contains great dangers as well as unlimited possibilities. It is the need to achieve this transformation in the best way, and to secure the intelligent utilization of science at every stage in it, that is the strongest reason for the study of the relations of science and society in the past, for only through this study can it be adequately understood.

Aspects of science

Before beginning this inquiry something must be said on the meaning and scope of science itself. Now of course it might seem most natural and convenient to start with a definition of science. Professor Dingle, in his extensive review [1.24] of my

book *The Social Function of Science*, demands that this should be done. According to him, the writer should begin

> by identifying this phenomenon and delineating as clearly as possible what it was in itself, apart from any function it might have or any relation in which it might stand to other phenomena; and he would then proceed to consider the part it played, or could play, in social life.

My experience and knowledge have convinced me of the futility and emptiness of such a course. Science is so old, it has undergone so many changes in its history, it is so linked at every point with other social activities, that any attempted definition, and there have been many, can only express more or less inadequately one of the aspects, often a minor one, that it has had at some period of its growth. Einstein [1.26] has put this point in his own way:

> Science as something existing and complete is the most objective thing known to man. But science in the making, science as an end to be pursued, is as subjective and psychologically conditioned as any other branch of human endeavour—so much so, that the question "what is the purpose and meaning of science?" receives quite different answers at different times and from different sorts of people.

To a human activity which is itself only an inseparable aspect of the unique and unrepeatable process of social evolution, the idea of definition does not strictly apply[1.4] (p. 875).

More than any other human occupation, science is, by its very nature, changeable. It is also, as one of the latest achievements of humanity, changing most rapidly. Nor has it long had a separate existence. At the dawn of civilization it was only one aspect of the work of the magician, the cook, or the smith. It was not until the seventeenth century that it began to achieve an independent status; and that independence may itself be only a temporary phase. In the future it may well be that scientific knowledge and method will so pervade all social life that science will once again have no distinct existence. Since a definition is intrinsically impossible, the only way of conveying what is being discussed in this book as science will need to be an extensive and unfolding description. This will be the task of the later chapters, but here, as a clue to the more detailed treatment, is an attempt to analyse in a few words the major aspects in which science appears in the contemporary world.

Science may be taken, (1.1) as an institution; (1.2) as a

method; (1.3) as a cumulative tradition of knowledge; (1.4) as a major factor in the maintenance and development of production; and (1.5) as one of the most powerful influences moulding beliefs and attitudes to the universe and man. In 1.6 the interactions of science and society are discussed. By listing these different aspects of science I do not intend to imply that there are as many different "sciences." With any concept so wide-ranging in time, connection and category, multiplicity of aspect and reference must be the rule. The word science or scientific has a number of different meanings according to the context in which it is used. Professor Dingle took the trouble to list ten of these taken from my book. In one case cited by him science is being contrasted with engineering, a matter of the degree of practical application; in another, the scientific method as a means of verification is contrasted with the intuitive recognition of discovery. All are significant uses of the word science, but to extract the full meaning from them, they need to be linked together in a general picture of the development of science. Of the aspects listed above, those of science as an institution and as a factor in production belong almost exclusively to modern times. The method of science and its influence on beliefs date back to Greek times, if not earlier. The tradition of knowledge passed on from parent to child, from master to apprentice, is the very root of science, existing from the earliest ages of man and long before science could be considered as an institution, or could have evolved a method distinct from common sense and traditional lore.

1.1—*SCIENCE AS AN INSTITUTION*

Science as an institution in which hundreds of thousands of men and women find their profession is a very recent development. It is only in the twentieth century that the profession of science has come to compare in importance with the far older professions of the Church and the Law. It is also being recognized as something distinct from, though allied to, those of medicine and engineering, which are themselves becoming at the same time less dependent on tradition and more permeated by science. Its growing association with the specialized professions has tended to accentuate the separation of science from the common avocations of society. We shall have much to say in later chapters of the origin of this separa-

tion and of its dependence on the economic functions of science. It is sufficient here to draw attention to the fact that it exists most markedly in capitalist countries. Today, to many people outside its discipline, science appears to be an activity carried on by a sort of people, the scientists. The word itself is of no great age. Whewell first used the word "scientist" in 1840 in his *Philosophy of the Inductive Sciences*: "We need very much a name to describe a cultivator of science in general. I should incline to call him a Scientist." These people are thought of as rather set apart: some working in obscure and inaccessible laboratories with strange apparatus, others occupied in intricate calculations and arguments, and all using languages which only their colleagues understand. This attitude has, in fact, some justification; while science grows and influences our daily lives more and more, it is not becoming more readily understandable. The actual practitioners of the several sciences have, in the course of time, moved almost imperceptibly into realms where they find it necessary to create special languages to express the new things and relations that they discovered, and have in the main not bothered to translate even the more interesting part of their work into ordinary language. Science has already acquired so many of the characters of an exclusive profession, including that of long training and apprenticeship, that it is popularly more easy to recognize a scientist than to know what science is. Indeed, an easy definition of science is *what scientists do*.

The institution of science as a collective and organized body is a new one, but it maintains a special economic character that was already there in the period when science was advanced by the separate efforts of individuals (p. 287). Science differs from all other so-called free professions in that its practice has no immediate economic value. A lawyer can plead or give a judgment, a doctor can cure, a minister can conduct a marriage or give spiritual consolation, an engineer can design a bridge or a washing machine—all things for which people are willing to pay on the spot. They are to that extent free professions in that they can demand what the market can bear. The separate productions of science, apart from certain immediate applications, are not saleable, even though in the aggregate and in a relatively short time they may, by incorporation into technique and production, bring into being more new wealth than all the other professions combined. As a

result, the problem of how to live has always been the first preoccupation of the scientist, and the difficulty of solving it has in the past been the primary cause that has held up scientific advance and is still, though to a lesser degree, holding it up today (p. 904).

In earlier times science was largely a part-time or spare-time occupation of people of wealth and leisure, or of well-off members of the older professions. The professional court astrologer was as often as not also the court physician (p. 197). This inevitably made it a virtual monopoly of the upper or middle classes. Ultimately both the tasks and rewards of science derive from social institutions and traditions, including, with more and more importance as time goes on, the institution of science itself. This is not necessarily a derogation of science. The social direction of science has been, at least until the recent drive for its militarization, a general and unexacting one, and may actually help an imaginative mind by forcing it to keep its attention on limited aspects of accessible experience. Thus, as we shall see (p. 334), the search for the longitude was a fertile social directive in the physics and astronomy of the seventeenth and eighteenth centuries, as was the search for antibiotics in the twentieth.

The real derogation of science is the frustration and perversion that arise in a society in which science is valued for what it can add to private profit and the means of destruction (pp. 583 f.). Not unnaturally, however, those scientists who see in such ends the only reason for which the society in which they live supports science, and who can imagine no other society, feel strongly and sincerely that all social direction of science is necessarily evil. They long for a return to an ideal state, which in fact never existed, where science was pursued purely for its own sake. Even G. H. Hardy's definition of pure mathematics, "This subject has no practical use; that is to say, it cannot be used for promoting directly the destruction of human life or for accentuating the present inequalities in the distribution of wealth," has been belied by events. For both of these results have, during and since the last war, flowed from its study. In fact at all times the individual scientist has needed to work in close connection with three other groups of persons: his patrons, his colleagues, and his public.

The function of the patron, whether a wealthy individual, university, corporation, or a department of State, is to provide

the money on which the scientist must live and which will enable him to carry on his work. The patron will in return want to have something to say in what is actually done, especially if his ultimate object is commercial advantage or military success. It will apparently be less so only if he is operating from pure benevolence or in the pursuit of prestige or advertisement; then he will only want results to be sufficiently spectacular and not too disturbing.

In a Socialist society the function of the patron is taken over by the organs of popular government at all levels, from the factory or farm laboratory to the academy institute, and is radically changed in the process. Because such a government can, and indeed necessarily must, take a long-term view, the work of scientists is accepted as intrinsically valuable. Their support and the furthering of their work are a first charge on national and local revenues. In return the scientists are expected to understand their social responsibility, which is to co-operate in the plans for a better society, and so to order their work as to get the best results on both a long-term and short-term basis.

In general the scientist has to " sell " his project to the patron, but he is unlikely to do so unless he can count on at least the tacit support of some of his fellow scientists, through the various institutions and societies to which they belong. These bodies have the duty of maintaining the intellectual status of science, but they do not, and cannot, except where science is planned, exercise much initiative in determining the fields of science that are to be studied, nor how much or how little work is to be done in them.

In the last resort it is the people who are the ultimate judges of the meaning and value of science. Where science has been kept a mystery in the hands of a selected few, it is inevitably linked with the interests of the ruling classes and is cut off from the understanding and inspiration that arise from the needs and capacities of the people. Bishop Sprat in his *History of the Royal Society* (1667) asks himself the question: Why have " the *Sciences of mens brains,* been subject to be far more injur'd by such vicissitudes, than the *Arts of their hands*? " He concludes that it was because they had been " banish'd, by the Philosophers themselves, out of the World. . . . Whereas if at first it had been made to converse more with the senses, and to assist familiarly in all occasions of *humane* life; it would, no doubt,

have been thought needful to be preserv'd, in the most *Active*, and *ignorant* Time. It would have escap'd the fury of the Barbarous people; as well as the Arts of *Ploughing, Gard'ning, Cookery, making Iron and Steel, Fishing, Sailing,* and many more such necessary handicrafts have done." If to this is added, as it has been throughout the later stages of the development of capitalism, the use of science to intensify manual work, to create unemployment, and to make war, there is an inevitable growth of suspicion and hostility to science on the part of the workers (p. 395). Science developing in this way is a limited science, hardly even a half-science, compared with its potential when it is an understood and valued part of a fully popular movement.

Any full understanding of science as an institution can come only after it has been studied from its origins in earlier institutions. It will be necessary to study the changes that it has undergone, especially in recent years, and to show how, as an institution, it interacts with others and with the general workings of society.

1.2—*THE METHODS OF SCIENCE*

The institution of science is a social fact, a body of people bound together by certain organizing relations to carry out certain tasks in society. The method of science is by contrast an abstraction from these facts. There is a danger of considering it as a kind of ideal Platonic form, as if there were one proper way of finding the Truth about Nature or Man, and the scientists' only task was to find this way and abide in it. Such an absolute conception is belied by the whole history of science, with its continual development of a multiplicity of new methods. The method of science is not a fixed thing, it is a growing process. Nor can it be considered without bringing out its closer relations with the social, and particularly the class, character of science. Consequently, scientific method, like science itself, defies definition. It is made up of a number of operations, some mental, some manual, that in the past have been found to lead to the formulation, finding, testing, and using of the answers to the general questions that are worth asking and can be answered at any stage of social development. In the distant past the questions that could usefully be answered were mostly in the fields of the mathematical sciences, such as astronomy and physics. In all other fields there were only

particular results found by experience and guaranteed by technical usefulness. Later, the scientific method came to be applied and modified in the fields of chemistry and biology, and now, in our own time, we are just beginning to learn how to apply it to problems of society.

Now the study of the method of science has proceeded much more slowly than the development of science itself. Scientists find out things first, and then, rather ineffectively, muse on the way in which they were discovered. Unfortunately, most of the books written about the methods of science have been by people who, though philosophically or even mathematically gifted, are not experimental scientists and strictly speaking do not know what they are talking about (pp. 527 f.).

Observation and experiment

The methods used by working scientists have evolved from a separation of methods used in ordinary life, particularly in the manual trades. First you have a look at the job and then you try something and see if it will work. In more learned language, we begin with *observations* and follow with *experiments.* Now everyone, whether he is a scientist or not, observes; but the important things are what to observe and how to observe them. It is in this sense that the scientist differs from the artist. The artist observes in order to transform, through his own experience and feeling, what he sees into some new and *evocative creation.* The scientist observes in order to find things and relations that are as far as possible independent of his own sentiments. This does not mean that he should have no conscious aim. Far from it; as the history of science shows, some objective, often a practical one, is almost an essential requirement for the discovery of new things. What it does mean is that in order to achieve its goal in the inhuman world, deaf to the most emotional appeal, desire must be subordinated to fact and law.

Classification and measurement

Two techniques have in time grown out of naïve observation: *classification* and *measurement.* Both are, of course, much older than conscious science, but they are now used in quite a special way. Classification has become in itself the first step towards understanding new groups of phenomena. They have to be put in order before anything can be done with them. Measurement is only one further stage of that putting in order. Counting

is the ordering of one collection against another; in the last resort against the fingers. Measuring is counting the number of a standard collection that balance or line up with the quantity that is to be weighed or measured. It is measurement that links science with mathematics on the one hand, and with commercial and mechanical practice on the other. It is by measurement that numbers and forms enter science, and it is also by measurement that it is possible to indicate precisely what has to be done to reproduce given conditions and obtain a desired result (pp. 79, 122).

It is here that the active aspect of science comes into the picture—that characterized by the word "experiment." An experiment, after all, as the word indicates, is only a trial, and early experiments indeed were full-scale trials. Once measurement was introduced it was possible not only to reproduce trials accurately, but also to take the somewhat daring step of carrying them out on a small scale. It is that small-scale or model experiment that is the essential feature of modern science. By working on a small scale far more trials can be carried out at the same time and far more cheaply. Moreover, by the use of mathematics, far more valuable results can be obtained from the many small-scale experiments than from one or two elaborate and costly full-scale trials. All experiments boil down to two very simple operations: taking apart and putting together again; or, in scientific language, *analysis* and *synthesis*. Unless you can take a thing or a process to bits you can do nothing with it but observe it as an undivided whole. Unless you can put the pieces together again and make the whole thing work, there is no way of knowing whether you have introduced something new or left something out in your analysis.

Apparatus

In order to carry out these operations, scientists have, over the course of centuries, evolved a complete set of material tools of their own—the *apparatus* of science. Now apparatus is not anything mysterious. It is simply the tools of ordinary life turned to very special purposes. The crucible is just a pot, the forceps a pair of tongs. In turn, the apparatus of the scientist often comes back into practical life in the form of useful instruments or implements. It is not very long, for instance, since the modern television set was the cathode-ray tube, a purely scientific piece of apparatus devised to measure the mass

of the electron. Scientific apparatus fulfils either of two major functions: as scientific instruments, such as telescopes or microphones, it can be used to extend and make more precise our sensory perception of the world; as scientific tools, such as micro-manipulators, stills, or incubators, it can be used to extend, in a controlled way, our motor manipulation of the things around us.

Laws, hypotheses, and theories

From the results of experiments, or rather from the mixture of operation and observation that constitutes experiments, comes the whole body of scientific knowledge. But that body is not simply a list of such results. If it were, science would soon become as unwieldy and as difficult to understand as the Nature from which it started. Before these results can be of any use, and in many cases before they can even be obtained, it is necessary to tie them together, so to speak, in bundles, to group them and to relate them to each other, and this is the function of the logical part of science. The arguments of science, the use of mathematical symbols and formulæ, in earlier stages merely the use of names, lead to the continuous creation of the more or less coherent edifice of scientific *laws, principles, hypotheses,* and *theories.* And that is not the end; it is here that science is continually beginning, for, arising from such hypotheses and theories, there come the practical *applications* of science. These in turn, if they work, and even more often if they do not, give rise to new observations, new experiments, and new theories. Experiment, interpretation, application, all march on together and between them make up the effective, live, and social body of science.

The language of science

In the process of observation, experiment, and logical interpretation, there has grown up the *language,* or, rather, the languages, of science that have become in the course of time as essential to it as the material apparatus. Like the apparatus, these languages are not intrinsically strange, they derive from common usage and often come back to it again. A cycle was once *kuklos,* a wheel, but it lived many centuries as an abstract term for recurring phenomena before it came back to earth as a bicycle. The enormous convenience of making use of quite ordinary words in the forgotten languages of Greece and

Rome was to avoid confusion with common meanings. The Greek scientists were under the great disadvantage of not having a word—in Greek—for it. They had to express themselves in a roundabout way in plain language—to talk about the submaxillary gland as "the acorn-like lumps under the jaw." But these practices, though they helped the scientists to discuss more clearly and briefly, had the disadvantage of building up a series of special languages or jargons that effectively, and sometimes deliberately, kept science away from the ordinary man. This barrier, however, is by no means necessary. Scientific language is too useful to unlearn, but it can and will infiltrate into common speech once scientific ideas become as familiar adjuncts of everyday life as scientific gadgets (p. 905).

The strategy of science

This discussion of the method of science has been limited so far to what might be called the *tactics* of scientific advance. This is primarily a method of solving problems and being reasonably sure that the solutions are satisfactory. It is clearly insufficient by itself to explain the advance of science as a whole over long periods of time. To complete the picture it is necessary to say something of what corresponds to the *strategy* of science. Now, of course, there is no absolute need for science to have a conscious strategy in order to advance, and indeed in earlier times it certainly was not directed with any long-term ends in view. Nevertheless, as we shall see, the path of advance of science was by no means a random one, and all the time something like a strategy must have been operating, unconsciously for the most part, but sometimes consciously as well.

The essential feature of a strategy of discovery lies in determining the sequence of choice of problems to solve. Now it is in fact very much more difficult to see a problem than to find a solution for it. The former requires imagination, the latter only ingenuity. This is the sense of Kosambi's definition of science as the *cognition of necessity*. The general advance of science has, in fact, taken place in following out the solutions of problems set in the first place by actual economic necessity, and only in the second place arising out of earlier scientific ideas. At any given time there are usually a set of challenging problems like the doubling in bulk of the cubic altar at Delphi, which involved extracting a cube root, or the finding of the longitude, which led to Newton's laws, or the curing of the silkworm disease

in France, which helped Pasteur to arrive at the idea of the germ theory of disease. The danger in science is that the number of such recognized classical problems tends to be limited. The efforts of scientists, generation after generation, are concentrated on solving them and on elaborating on the solutions.

It is this tendency that has kept science for long periods of its history within narrow bounds. It is by breaking with it and finding new problems in outside life that it expands into new fields. Some of the greatest scientists of the past, like Newton, Darwin, and Faraday, set themselves to find and solve problems according to a plan of their own. Faraday,[5.32] for instance, early in his career set himself the general problem of finding the connections between the separate forces of physical Nature—light, heat, electricity, and magnetism—and taking them pair by pair, nearly completed the programme (p. 439).

Now we are beginning to see that what could be done consciously, though on a small scale, by such great individuals is an essential part of the growth of science, and we are finding it possible to plan science consciously on a collective rather than a purely individual basis. Here the wider problem comes from the need to reconcile and combine the questions arising from the social and economic requirements on the one hand, and the intrinsic developments of science on the other. This, however, involves, for its full advantages to be discovered and used, a far greater control over the economic life of the country than is to be found outside Socialist countries. These advantages are, nevertheless, so great in the long run that no nation will be able to hold its own in the world without making positive and planned use of science. Consequently, the advance of science and its increasing utilization in social life are likely in the future to take a far more rational and less accidental course than in the past.

Viewed in the perspective of evolutionary history, science marks a conscious elaboration of the experience provided by the sensory and motor organs of the body. It extends consciously and socially the unconscious processes of learning, common to all higher animals. An animal can learn by experience; man in using science goes beyond this and experiences to learn. In the same sense the scientific method itself, with its codified processes of comparison, classification, generalization, hypothesis, and theory, is an extension of the mechanism of the brain, which had already evolved in the higher mammals the capacity of dealing with highly complex situations, such as

those involved in hunting. The essential difference, however, between these animal performances and the achievements of human science is that the latter is no longer an individual but a social achievement. It arises from the co-operative effort of *work* and is co-ordinated by *language*.

Science and art

The extension of the physical powers of man through science is no longer, as in animals, a continuous, almost automatic, evolutionary process. It comes about as a necessary correlate of social changes and is marked by the same internal struggles and conflicts of successively emerging classes. Bearing always in mind the inseparability of science from society, it may yet be useful to abstract still further and to consider the features of science which distinguish it from other aspects of human social activity, such as those of art or religion. The major grounds for the distinction of the scientific aspect are that it is concerned primarily with *how* to do things; that it refers to a cumulative mass of knowledge of fact and action; and that it arises first and foremost in the understanding, control, and transformation of the means of production—that is of techniques for providing human needs.

The first of these distinctions can be expressed by saying that the mode of science is *indicative*, in that it can indicate or show people how to do what they want to do. In itself the *scientific mode* does not attempt to make people want to do one thing rather than another. That is more properly the task of the *artistic mode*, a mode equally social, one of whose functions it is to generate first the wish and then the will for specific action.[1.2.146] Neither of these modes is complete without the other and, in fact, neither in science nor in art is one to be found without the other. Nor between them do they exhaust the significance of art or science for the individual. Beyond them, and common to all forms of human achievement, is the intrinsic pleasure produced in the contemplation, or still more in the creation, of new combinations of words, sounds, or colours, or in the discovery of combinations already existing in Nature. This pleasure, though felt individually in the first place, is by no means a private emotion. As the first interest derives from society, so the contemplative act is social at one remove, as is shown by the intense desire, common to artist and scientist, to communicate it.*

Every work of science has a purpose and generates a further purpose, but that purpose is not the characteristically scientific aspect of the work, neither is it the beauty or pleasure to be appreciated in the work of science. In its purely scientific aspect, it is a recipe: it tells you how to carry out certain things if you want to do them. Nor, on the other hand, is a work of art something that merely moves or pleases. Works of art themselves contain invaluable information about the world and how to live in it, especially when, as in the novel, they deal with social problems.

In stating these abstract characteristics of science, there is always the danger that the abstract may be taken as the ideal, that is, what science should be if only all the unessential aspects of social morality or usefulness could be removed. Indeed, the ideal of pure science—the pursuit of Truth for its own sake—is the conscious statement of a social attitude which has done much to hinder the development of science and has helped to put it into obscurantist and reactionary hands (p. 138). It should always be remembered that science is complete only if the indications are followed. Science is not a matter of thought alone, but of thought continually carried into practice and continually refreshed by practice (pp. 873 f.). That is why science cannot be studied separately from technique. In the history of science we shall repeatedly see new aspects of science arising out of practice and new developments in science giving rise to new branches of practice. The professions of the modern engineer are very largely directly due to scientific progress. The very names of the different kinds of engineers there are today, electrical engineers, chemical engineers, radio engineers, indicate that they were all originally branches of science that have now become branches of practice.

Scientist and engineer

But the fact that the engineers have arisen from the scientists, and are continually and closely linked with them, does not mean that the two professions are indistinguishable. In fact, the functional aspects of the scientist and the engineer are radically different. The scientist's prime business is to find out how to do things, the engineer's is to get them done. The responsibility of the engineer is much greater, in the practical sense, than that of the scientist. He cannot afford to rely so much on abstract theory; he must build on the traditions of past experience

as well as try out new ideas. In certain fields of engineering, indeed, science still plays a subsidiary role to experience. Ships today, although full of modern scientific devices in their engines and controls, are still built by men who have based their experience on those of older ships, so that one may say that the building of ships, from the first dug-out canoe to the modern liner, has been one unbroken technical tradition. The strength of technical tradition is that it can never go far wrong—if it worked before, it is likely to work again; its weakness is that it cannot, so to speak, get off its own tracks. Steady and cumulative improvement of technique can be expected from engineering; but notable transformations, only when science takes a hand. As J. J. Thomson once said, " Research in applied science leads to reforms, research in pure science leads to revolutions."[6.58a.199] At the same time engineering successes, and even more engineering difficulties, furnish a continually renewed field of opportunity and problems for science. The complementary roles of science and engineering mean that both need to be studied to understand the full social effects of either.

1.3—*THE CUMULATIVE TRADITION OF SCIENCE*

So far, in discussing the institution and character of science, we have not explicitly stressed one aspect that distinguishes scientific and technical advance from all other aspects of social achievement. This feature of the sciences is their cumulative nature. The methods of the scientist would be of little avail if he had not at his disposal an immense stock of previous knowledge and experience. None of it probably is quite correct, but it is sufficiently so for the active scientist to have advanced points of departure for the work of the future. Science is an ever-growing body of knowledge built of sequences of the reflections and ideas, but even more of the experience and actions, of a great stream of thinkers and workers. To know what is known is not enough; to call himself a scientist, a man needs to add something of his own to the general stock. Science at any time is the total result of all that science has been up to that date. But that result is not a static one. Science is far more than the total assembly of known facts, laws, and theories. It is a continual discovery of new facts, laws, and theories, criticizing and often destroying as much as building. Nevertheless, the whole edifice of science never stops growing.

It is permanently, as we may say, under repair; but it is always in use.

It is this cumulative nature that marks off science from the other great human institutions, such as those of religion, law, philosophy, and art. These, of course, have histories and traditions far longer than those of science, and to which far greater attention and respect are paid, but they are not in principle cumulative. Religion is concerned with the preservation of "eternal" truth, while with art it is the individual performance rather than the school that matters. The scientist, on the other hand, is always deliberately striving to change accepted truth, and his work is very soon assimilated, superseded, and lost as an individual performance. Not only the artists and poets themselves, but whole peoples look at, hear, or read the great works of art, music, and literature of the past in the original or in close reproduction or translation. They are, by virtue of their direct human appeal, always alive. By contrast, only a small minority of scientists and scientific historians, and hardly anyone else, study the great historic works of science. The results of these works are incorporated in current science, but originals are buried. It is the established relations, facts, laws, and theories, that matter for most purposes, not the manner of their discovery or first presentation.[1.17] There is, moreover, a profound difference of another kind between the tradition of the sciences, particularly of the natural sciences, and those of religion or of the liberal arts. The latter are arbitrary in the sense that their final court of appeal is a revelation or judgment handed down by oral or written tradition. In so far as they lay claim to a rational justification, it is one of idealist logic. On the other hand, the tradition of science, and with it that of technology, from which it arose, is one which can be directly checked by reference to verifiable and repeatable observations in the material world. However old or new, each acquisition of science can be subjected at any time to tests on determinate materials with determinate apparatus. The truth of science, as Bacon pointed out long ago (p. 306), is the success of its application to material systems, whether inanimate, as in the physical sciences; living organisms, as in the biological sciences; or human societies, as in the social sciences. It is only in so far as in the last of these there is little or no experiment that it has not yet gained the status of a true science (pp. 695 f.). By sciences in this sense we refer necessarily

to those parts of human knowledge which are sufficiently developed to be used to improve practice directly and are not merely orderly descriptions of obvious facts. It is unquestionable that the Greeks had a biology and even a sociology as well as mathematics and astronomy; but whereas the latter two could be used for the planning of towns and the prediction of heavenly events, the former only explained to the learned in an orderly fashion what was known to every farmer, fisherman, or politician. Scientific biology of real use to medicine was hardly to appear before the nineteenth century, and scientific sociology is only just beginning.

The stages by which the accumulation of scientific knowledge and techniques has taken place will be described, though not discussed in detail, in subsequent chapters. This is properly the task of a history of science, which this book does not claim to be, though such a critical history of science, going beyond the facts of discovery to ascertain the reasons, has yet to be written. Here it is sufficient to indicate some of the general principles that have ruled the building of the edifice of science.

The pattern of scientific and technical advance

In the first place, history shows a definite succession of the order in which regions of experience are brought within the ambit of science. Roughly it runs: mathematics, astronomy, mechanics, physics, chemistry, biology, sociology. The history of techniques follows an almost inverse order: social organization, hunting, domestic animals, agriculture, pottery, cooking, cloth-making, metallurgy, vehicles and navigation, architecture, machinery, engines. The reason for this is easy to see. Techniques must first arise from man's concern with his biological environment and only gradually pass to the control of inanimate forces. The actual order of the development of the sciences, on the other hand, is not so easy to explain. It is only partly conditioned by internal difficulties. In fact, as their histories show, the sciences of the more complex parts of Nature, such as biology and medicine, were derived directly by study of their subject-matter, with little help and often much hindrance from the sciences of the simpler parts, such as mechanics and physics (pp. 333, 469). The time sequence of the sciences fits even more closely the possibly useful applications which were in the interest of ruling or rising classes at different times. The regulation of the calendar—a priestly function—gave rise

to astronomy (p. 82); the needs of the new textile industry—the interest of the rising manufacturers of the eighteenth century—gave rise to modern chemistry (p. 374).

If we turn from the general paths of advance in science to the detailed sequences of discovery, certain general patterns appear. In any particular field there are found long chains of successive discoveries—like those, for example, of electricity in the eighteenth century (pp. 431 f.), or of atomic physics in the twentieth (pp. 515 f.). These usually start and end with some crucial discovery that opens up whole new ranges of science. Such discoveries occur most often through the coming together of scientific disciplines previously thought to be distinct, as occurred, for example, in Oersted's accidental discovery of the effect of electricity on a magnet (p. 437), or in Pasteur's chance discovery of the asymmetric nature of molecules produced by living organisms (p. 455), which linked chemistry with bacteriology. From each of these intersections of disciplines or crucial discoveries of science there usually spring two or three new branches, each of which can continue as a new chain of discovery. The whole of the picture is therefore like an indefinitely complicated interlacing of investigation and discovery, something like the ancient Peruvian *quipu* which conveyed messages by sequences of knots on cords, themselves complexly knotted together (p. 878).

The role of great men

Both the long chains of investigations and the branching points of crucial discoveries are essential to the progress of science, but whereas the former are the fruit, for the most part, of the application of numbers of painstaking but ordinary minds, the latter are usually associated with the great men of science. This has led to a concept of science as if it were due solely to the genius of great men, and were consequently largely divorced from the effect of social and economic factors. The hold of the "great men" myth on the history of science has indeed lasted far longer than in social and political history. Many histories of science are, in fact, little more than the stories of great discoverers to whom came in a kind of apostolic succession epoch-making revelations of the secrets of Nature. Now great men have had decisive effects on the progress of science, but their achievement cannot be studied in isolation from their social environment. It is through failure to see this that it is

so often felt necessary to explain their discoveries by resorting to "know nothing" words such as "inspiration" or "genius." Great men are thus lessened in stature and cheapened by those too limited or too lazy to understand them. The fact that they are men of their time, subject to the same formative influences and suffering the same social compulsions as other men, only enhances their importance. The greater the man, the more he is soaked in the atmosphere of his time; only thus can he get a wide enough grasp of it to be able substantially to change the pattern of knowledge and action.

Nor is the great man self-sufficient in any cultural field, least of all in science. For no discovery of any effective kind can be made without the preparatory work of hundreds of comparatively minor and unimaginative scientists. These latter accumulate, most often without understanding what they are doing, the necessary data on which the great man can work. Individual human beings have an enormous range of mental variation. Only a few are likely to contribute to science, though more have the opportunity of doing so in our time than ever before and far more are likely to do so in the near future. Those selected or selecting themselves for scientific interest are likely to differ in almost all other particulars. This gives a great variety to science, but the equally necessary unity comes from the controls, unconscious or conscious, that society exercises on it. It is this socially imposed unity of science that makes it possible to see it as one co-operative effort of man to understand and thus control his environment (p. 878).

1.4—*SCIENCE AND THE MEANS OF PRODUCTION*

All the characteristics given in the preceding paragraphs may serve to describe science—as an institution, as a method, as a growing and increasingly organized collection of experiences. By themselves, however, they cannot explain either the major functions of science today or the reasons why science originally arose as a specialized kind of social activity. This explanation is to be found in the part that science has played in the past and plays today in every form of production. The history of the elaboration of man's means of control over his inorganic and organic environment, as it will be sketched in succeeding chapters, shows that this has taken place in stages, each marked by the appearance of some new material technique. Even

now in archæological terms (first put forward by Thomsen in 1836 but founded on traditions of great antiquity passed on by Hesiod and Lucretius) we describe the eras of the past in terms of materials—the Stone Age, the Bronze Age, the Iron Age (though we have lost the Golden Age). We continue with the ages of steam and electricity, and have now entered the atomic age.

Materials in themselves, however, are no use to man; he must learn to fashion them. Even the original material (*madera*—wood—*hyle*) had to be torn from the tree to make a club or a spear. It was in the ways of extracting and fashioning materials so that they could be used as tools to satisfy the prime needs of man that first techniques and then science arose. A technique is an individually acquired and socially secured way of doing something; a science is a way of understanding how to do it in order to do better. When we come to examine in greater detail, in later chapters, the first appearance of distinct sciences and the stages of their development it will become increasingly plain that they evolve and grow only when they are in close and living contact with the mechanism of production.

Science has had a history of remarkable unevenness; great bursts of activity are followed by long fallow periods until a new burst occurs, often in a different country. But the where and when of scientific activity are anything but accidental. Its flourishing periods are found to coincide with economic activity and technical advance. The track science has followed—from Egypt and Mesopotamia to Greece, from Islamic Spain to Renaissance Italy, thence to the Low Countries and France, and then to Scotland and England of the Industrial Revolution—is the same as that of commerce and industry. In earlier times science followed industry; now it is tending to catch up with it and lead it as its place in production becomes clearly understood. Science was learned from the wheel and the pot; it created the steam-engine and the dynamo (pp. 414 f., 440 f.).

Between the bursts of activity there have been quiet times, sometimes periods of degeneration such as that of the later Egyptian dynasties, or of late classical times, or of the early eighteenth century. These, we shall see, coincide with periods when the organization of society was stagnant or decadent, so that production followed traditional lines and concern with it was considered to be debasing for a man of learning.

Now the observation of the close association between science

and the technical change does not in itself explain the origin and growth of science; we still need to know the social factors determining the technical changes themselves. The converse relation of technical factors in society is obvious enough. The technical level of production at any period puts a limit to the possible forms of social organization. It would be useless to look for an extensive national State in the Stone Age, when food-gathering and hunting limited the effective social unit to a few hundreds ranging over a wide territory. Nor could the modern urban civilization arise until the combination of agricultural and industrial improvements made it possible to maintain a majority of the population away from the land (p. 369).

Nevertheless, changes in technique are not so simply determined by social organization. It would be very wide of the mark to assume that mankind has in the past acted as one intellectual unit, seeking always to use existing means to provide the best for all men and searching always for the best means of extending man's powers over Nature. In fact, as will be shown in the ensuing chapters, throughout the greater part of history improvements in technique have arisen mostly under the stimulus of the immediate advantage they would give to certain individuals or classes, often to the detriment of others, and sometimes, as in war—a perennial source of ingenuity—to their destruction. The form of society depends, in the last resort, on the relations between men in the production and distribution of goods—relations nearly always of undue advantage to the rich over the poor, and sometimes of direct compulsion, as in slavery.

As will be shown (Chapter 12), it is these *productive relations*, depending as they do on the technical *means of production*, that provide the need for changes in these means and thus give rise to science (pp. 738 f.). When the productive relations are changing rapidly, as when a new class is rising into a position of power, there is a particular incentive to improvements in production which will enhance the wealth and power of this class, and science is at a premium. Once such a class is established and is still strong enough to prevent the rise of a new rival, there is an interest in keeping things as they are—techniques become traditional and science is at a discount. Such a simplified picture is, of course, inadequate by itself to explain the rise of science in detail. To discover why a certain

science arose in this or that place or period requires far more detailed studies, examples of which will be found, though still only in outline, in the later chapters. It will also be necessary to bring out the interplay between the material factors—the availability of commodities such as wood or coal; the technical factors—the level and distribution of skills; and the economic factors—the supply and demand for goods or labour, in order to explain the rise and decline of science and, in turn, its effect on production.

The class character of early science

One basic distinction between science as such and the generalized techniques from which it arose and to which it is still attached is that it is essentially a literate profession. It is something recorded and transmitted in books and papers, as distinct from the handing on by practical example of the traditional crafts. As such, it was from the very start an occupation limited to the upper classes or to a minority of gifted individuals who managed to win acceptance into them in return for loyal service. This limitation has had several effects on the character of science. It has retarded it by keeping out of science the great majority of the naturally gifted people of all classes who might have contributed to it (p. 394). At the same time it has ensured that those thinking and even experimenting about science, at least until the time of the Industrial Revolution, should have had very little acquaintance with practical arts and so, in matters of natural science, have not known what they were talking about. Nor could they understand, because they did not themselves feel, the practical needs of common life and, therefore, they had no stimulus to satisfy them by the use of science.

This identification of science with the governing and exploiting classes has, from the earliest times of class division, which arose five thousand years ago with the first cities, engendered a deep suspicion of science, and book-learning generally, in the minds of the peasants and, to a lesser degree, of the working classes. However well intentioned were the efforts of the philanthropic philosophers, the people could not but feel that in practice they would result in changes that would bring them no good, and were likely to enslave them more completely or, alternatively, throw them out of work. The first scientists were regarded as magicians capable of unlimited mischief, and this

attitude persisted into late classical times when popular feeling, often allied with religion, was sullenly and sometimes violently against the philosophers who were identified, with some justice, with the interests of the upper classes (p. 167) of the hated Roman Empire. In the Middle Ages science existed only on sufferance, and even after its rebirth the same popular reaction was to be seen in the machine wreckers of the Industrial Revolution. Today we can still see it in the reactions to the latest triumph of science, the atom bomb. The combined effect of the contempt and ignorance of the learned, and of the suspicion and resentment of the lower orders, has been, through the whole course of civilization, a major hindrance to the free advance of science. It has replaced an unwilling and grudging co-operation for the free and active exchange of practical and theoretical knowledge that can, as experience in Socialist countries is now beginning to show, greatly increase the rate of technical and scientific advance.

This stricture applies only to the class character of the separation of theory and practice, and does not by any means imply any disparagement of the function of learning in advancing science. The fact that science was in the hands of persons who could write, keep accounts, and argue in set form, was at certain periods of inestimable value in its growth. Nature as a whole, taken in all its rawness and complexity, is difficult to argue about in mere words to any purpose. Myths and rituals justifying practices of proved utility are as far as such unlettered discourse can go. Even early formal science, such as that of the Greeks, was scarcely more than a rationalized mythology (p. 120). But certain parts of experience, like simple motions and forces, can be argued about formally and quantitatively. Sailors knew very well how to use levers and merchants to use balances many centuries before Archimedes discovered the formal law of the lever; but his law enabled new mechanical inventions to be made which would never have occurred to practical men. What is more, it was one step, and a very important one, in building further generalizations in mechanics and physics in the times of Galileo and of Newton. Stage by stage rational methods cease to be face-saving descriptions in a learned language and become means of generalizing and extending practical control over Nature, first in the chemical and biological, and now in the social field.

Nevertheless, as will be shown later (pp. 867 f.), the most important and fruitful periods of scientific advance were those in which the class barrier was at least partially broken down and the practical and the learned men mixed on equal terms. Such were the conditions in early Renaissance Italy, in France of the great Revolution, in America at the end of the nineteenth century, and, in a different and more thorough sense, so they are in the new Socialist republics of today.

Just because of its universality, the class nature of science is so much taken for granted that any mention of it today in scientific circles causes a shocked surprise. The tradition of science, they feel, is something in its own right, quite separate from any considerations of economics or politics. All that this means is that the social and, in particular, the class conditioning of the scientific tradition is implicit and does not show on the surface. In our own age, for the first time, science itself is being subjected to analysis on the basis of its class character. Much of this analysis has been crude and misdirected, confusing the actual achievements of science with the general theories built into them; nevertheless, it needs to be continued and refined and will lead in the end to a far deeper understanding of science and society.

1.5—*NATURAL SCIENCE AS A SOURCE OF IDEAS*

Though the practical utilization of science is both a perennial source of scientific advance and the guarantee of its validity, the advance of science is something more than the continual improvement of techniques. An equally essential part of science is the theoretical framework which links together the practical achievements of science and gives them an ever-increasing intellectual coherence. In the past, and even now, the history of science has often been written as if it were simply the history of such an ideal edifice of truth. Such history can only be written by neglecting the whole social and material components of science and thus reducing it to inspired nonsense, as has already been stated and will be illustrated fully in the body of the book.

On the other hand it would be equally stupid to attempt to neglect it entirely, for theory has had an enormously important part to play in science and in recent times an increasingly positive one. Indeed, over many periods of science the main

direction of work was conditioned by the proving, or, even more often, by the disproving, of theory as, for example, biology in the late nineteenth century, with the proving of the Darwinian theory of evolution (p. 604); or mechanics in the seventeenth, with the disproving of Aristotelian physics (pp. 295 f.). There is, however, an intrinsic danger in the development of such autonomous and closed fields of scientific endeavour. Though starting originally from practice they tend with time to become more and more divorced from it, and to lose, at the same time as losing their utility, any sense of direction. In the past they have usually petered out in learned pedantry, as did Newtonian mechanics in the nineteenth century (p. 384); or they have been revivified only by new contact with practice, as was electricity at the end of the eighteenth by the discovery of the electric battery (p. 435).

The conventional view of science describes its laws and theories as legitimate and even logical deductions from experimentally established facts. It is doubtful, if this limitation had been strictly insisted on, whether science would ever have existed. The laws, the hypotheses, the theories of science have a wider bearing than the objective facts they claim to explain. Most of them necessarily reflect in large part the general non-scientific intellectual atmosphere of the time by which the individual scientist is inevitably conditioned. The result is that the phenomena of Nature and of the manual arts are interpreted in social, political, or religious terms. Thus, as we shall see, Newton's theory of inertia came from the prevailing rational interpretation of religion, and Darwin's natural selection from the current conception of the natural justice of free competition.

Sometimes these forms of thought can lead to valid, that is practically verifiable, scientific advances. As often, especially when they win general acceptance, they are obstacles to scientific discovery. The greatest difficulty of discovery is not so much to make the necessary observations, but to break away from traditional ideas in interpreting them. From the time when Copernicus established the movement of the earth and Harvey the circulation of the blood, down to that when Einstein abolished the ether, and Planck postulated the quantum of action, the real struggle has been less to penetrate the secrets of Nature than to overthrow established ideas, even though these, in their time, had helped to advance science. Nevertheless, the progress of science depends on the

existence of a continuous traditional picture or working model of the universe, partly verifiable, but also partly mythical where verifications are delusive or altogether missing. It is, on the other hand, equally essential that this tradition, compounded as it is (and must always be) from elements drawn from both science and society, should be continually and often violently broken down from time to time and remade in the face of new experience in the material and social worlds.

We are passing through such a period at the present moment. The far greater part that science is playing in the economy of highly industrialized countries has, by no means accidentally, coincided with a great deepening and widening of understanding of natural phenomena, in which the discoveries of the structure of the atom and of the chemical processes in living organisms are outstanding. This in itself has put the theories of science under a severe strain and has resulted in a rapid sequence of appearances of radically new theories, such as those of relativity and quantum mechanics (pp. 524 f.).

At the same time, and largely due to the same factors, there have occurred rapid political and economic transformations, starting in the Soviet Union and now spreading over the rest of the world, with a radically different attitude to the relations of science and society in practice. This has inevitably had a profound effect on scientific theory, which is now being subjected to a critical analysis in the light of Marxist philosophy. This will be discussed in some detail in a later chapter (p. 820). As a result of these combined influences, from within and without science, there has never been a period when the theoretical foundations of science have been so much in question as they are today.

Materialism and idealism

The general character of the theoretical controversy inside science is, however, not new. As will emerge clearly from a study of its history, a sometimes latent, sometimes active, struggle has been going on ever since the dawn of science between two main opposing tendencies: one, formal and idealistic; the other, practical and materialistic. We shall see this conflict as the dominant one in Greek philosophy, but it must have originated much earlier, indeed from the first formation of class societies, for the general social affinities of the two sides in the conflict have never been in doubt.

The idealist side is the side of "order," the aristocracy, and established religion; its most persuasive champion is Plato. The objective of science, in its view, is to explain why things are as they are and how impossible, as well as impious, it is to hope to change them in essentials. In Plato's mind all that is necessary is to remove a few blemishes, such as democracy, for the republic to be established safely for ever under the care of the guardians, the "men of gold." As the perfections of this state of affairs may not be at once apparent to inferior ranks, it is necessary to prove to them the illusoriness of the material world and consequently the unreality of evil in it (p. 125). In this imagined world, change is evil; the ideal, the good, the true, and the beautiful are eternal and beyond question; and as they are palpably not very prevalent on earth they must be sought for in a perfect heaven. This view has had a profound effect on the development of science, particularly in astronomy and physics (p. 139), and even today, in more elaborate and sophisticated forms, there is again a strong tendency to enforce it on science (pp. 527, 531).

The materialist view, partly because of its practical nature and even more because of its revolutionary implications, did not for centuries find much support in literate circles and rarely formed part of official philosophy (p. 128). One expression of it, however, survives in Lucretius' Epicurean poem *De Rerum Natura* (On the nature of things), which shows both its power and its danger to established order. It is essentially a philosophy of objects and their movements, an explanation of Nature and society from below and not above. It emphasizes the inexhaustible stability of the ever-moving material world and man's power to change it by learning its rules. The classical materialists could go no further because, as we shall see, of their divorce from the manual arts; nor could, in later days, the great re-formulator of materialism, Francis Bacon. Once the Industrial Revolution was under way, science became in practice materialist, though continuing to give, for political and religious reasons, some lip service to idealism. Up to the middle of the nineteenth century materialism remained philosophically inadequate because it did not concern itself with society and its transformations, and was thus unable to account for politics and religion. The extension and transformation of materialism to include these was the work of Marx and his followers.[1.27] First effective in the political and

economic field, the new dialectical materialism is only now beginning to enter the sphere of the natural sciences.

The struggle between idealist and materialist tendencies in science has been a persistent feature in its history from earliest times. The idealism of Plato is in some sense an answer to the materialism of Democritus, the founder of the atomic theory (p. 127). In the Middle Ages, Roger Bacon attacked the prevailing Platonic–Aristotelian philosophy and preached a science aimed at practical utility (p. 226), and was imprisoned for his pains. In the great struggle of the Renaissance to create modern experimental science the prime enemy was formal Aristotelianism backed by the Church. The same opposition was to be found in the last century in the warfare between science and religion over Darwinian evolution. The very persistence of the struggle, despite the successive victories won by materialist science, shows that it is not essentially a philosophic or a scientific one, but a reflection of political struggles in scientific terms. At every stage idealist philosophy has been invoked to pretend that present discontents are illusory and to justify an existing state of affairs. At every stage materialist philosophy has relied on the practical test of reality and on the necessity of change.

1.6—*INTERACTIONS OF SCIENCE AND SOCIETY*

This completes the first brief survey of the general aspects of science, as an institution, a method, and a cumulative tradition, and of the description of its links with the forces of production, and with general ideology. It should now be apparent, without pressing for a definition, what is meant by science for the purposes of this book. At the same time it would be far too much to ask the reader to accept the conclusions stated and implied in these sections without the further evidence which it is the function of the rest of the book to provide. Indeed, it is only by a fairly detailed presentation of the interactions of science and society throughout history that we can even begin to understand what science means and what its future may hold.

Science and society have, in fact, interacted in a great number of different ways, and the tendency to insist on one or other of these has been the cause of much of the recent controversy as to their mutual relations. It is usual to begin with the influence of science on society: to think of some crucial

discovery, such as that of electromagnetic waves, being first of all theoretically predicted, then detected in scientific laboratories, next tried out on an engineering scale, and finally, as radio, becoming part of everyday life. But that is not the only, nor even the main way in which science grows and affects society. Even more often it happens that a scientist comes to notice the performance or the failure of some practical device. The scientist either disinterestedly, or very often with an idea of improving it, looks into it and discovers not necessarily how to make it work, but something quite different. He may indeed create a new branch of science, just as thermodynamics was founded from a study of the steam engine[5.3] (p. 419). What is important here is that common practical experience furnishes a magnet, so to speak, of scientific interest, and the progress of science can be followed in terms of successively changing fields of general economic and technical interest.

This book does not claim to be a history of science; its theme is essentially this interaction between science and society. If it has any bias, it is on the side of the influence of science on history rather than that of history on science—a theme on which much has already been written.[3.1; 4.1] But the effect of science on history has, in the past, largely been neglected, or at best dealt with in a perfunctory or misleading way. This is because the professional historians have not had, for the most part, the qualifications required to assess or even notice the contributions and influence of science; while on the other hand the historians of science have been little concerned with the wider historic consequences of the growth of natural knowledge. In official histories there has been a tendency to bring in the *state of science*, together with that of literature and art, as a kind of cultural appendage to a political, or now slightly economic, account of each historical period. What is needed instead is a discussion of the contributions of science to technique and to thought which should find its place in the very body of the narrative. To the extent that this is not done the essential *historical* character—that is the progressive and non-repetitive element—is lost from the exposition of history. We are left instead with an account of personal and institutional relations of society without any clue as to why they should not have been repeated indefinitely with variations. As clearly progressive trends cannot in fact be hidden, the non-scientific historian must blankly refuse to explain them or provide some mystical

explanation, either divine providence or an assumed law of the growth and decay of civilization of the type suggested by Spengler or Toynbee. It is only in the light of science that we can begin to understand the irreversible, novelty-producing steps that are characteristically *historical*.

As has already been indicated, and will appear in more detail in subsequent chapters, science influences history in two major ways: firstly by the changes in the methods of production that it brings about; and then by the more direct, but far less weighty, impact of its findings and ideas on the ideology of the period. It was the first of these that led to the emergence of science from technique on the one hand, and religion on the other. Once a means had been found, even in a limited sphere, of improving techniques by using organized thought ordered by logic and verified by experiment, the way was open to an indefinite influence of science in production methods. In turn these affect productive relations, and hence have an enormous influence on economic and political developments.

The other influence of science, through its ideas, was at least as early. Once formulated, scientific ideas return into the common stock of human thought. The great revolutions in man's understanding of the universe and of his place and purpose in it that have occurred in antiquity, through the Renaissance to modern times, have largely been brought about by science. It was the new reign of simple natural law inaugurated by Galileo and Newton which seemed to justify at the same time a turn to simple Deism in religion, *laisser-faire* in economics, and liberalism in politics. Darwin's natural selection, for all that it originated from such liberal ideology, was to be used in turn to justify ruthless exploitation and race subjection under the banner of the survival of the fittest. A more profound understanding of evolution was, on the contrary, to stress the way in which, through society, man could transcend the biological limits of animal evolution and achieve a more far-reaching, consciously directed, social evolution (pp. 763 f.).

In less obvious ways scientific knowledge and scientific method are affecting, to an ever-increasing degree, the whole pattern of thought, culture, and politics. Science is now becoming a great human institution, distinct from, though closely linked with, all the older human institutions. It differs from them only in that, being more recent, it is still in its actively growing phase and its position with regard to the rest of society

is not yet in equilibrium. Science has a long way to go in making its full weight felt in human affairs.

Throughout most of this book the emphasis will be on the natural rather than the social sciences, apart from the two chapters (12 and 13) devoted to them. This is because, until very recently and under the influence of Marxism, the discussion of human relations in society, itself almost the earliest of the fields of human knowledge, had not emerged from the trammels of magic and religion. In more recent times, as we shall see (p. 689 f.), the nascent social sciences have been reduced almost to impotence through the fear that they might be used to analyse and alter the economic and political bases of capitalism. It is partly for this reason that the social changes, brought about through the effect of the natural sciences on the mode of production, have been neither planned nor understood and have often had, indeed are still having, disastrous results. It is only by the welding of a genuine social science with natural science that a satisfactory and progressive social control of social activities can be secured.

Mankind has had at all times a "Great Tradition," comprising the basis for what at different times has been deemed to be true belief and right action. This tradition, ever since it can be recognized as emerging from the dim past of prehistory, is essentially one, though we can discern partly independent branches in the Mediterranean countries, in India, and in China. The growth and change of this great tradition cannot be understood without science, but equally, science cannot be understood unless it is seen as a natural part of the common tradition.

The remainder of this book represents an attempt to illustrate, by a consideration of different periods and sciences, the general place of science in cultural history. According to the plan already set out in the preface, this will follow, in increasing scale and detail, the whole course of science from its first appearance to the present day. As the story is told it should be easier to understand the compressed and abstract relationships that have been set out in this chapter, and to see how they emerge naturally from the very experience of human history.

PART II
SCIENCE IN THE ANCIENT WORLD

INTRODUCTION

BEFORE we can understand science as we know it today, a social institution with its own tradition and its own characteristic methods, it is first of all necessary to look into its origins. Now the study of the origins of science presents a double problem. First there is the difficulty, inherent in all studies of origin, that as we go farther back and reach the critical periods where the basic innovations were made, it becomes harder to find out what actually happened. But there is an additional difficulty in the case of science, due to the fact that science does not appear in the first place in a recognizable form, but has to be gradually distinguished from more generalized aspects of the cultural life of the times. It is necessary to search for its hidden sources in the histories of human arts and institutions.

Because the essential character of natural science is its concern with the effective manipulations and transformations of matter, the main stream of science flows from the techniques of primitive man, which must be shown and imitated, not learned by rote. The expression of science is, however, initially verbal and later written, and consequently the ideas and theories of science are drawn from social life and come in turn from magic, religion, and philosophy.

The influence of the culture of ancient times affects our culture today through an unbroken chain of tradition of which only the latter part is a written tradition. The whole of our elaborate mechanical and scientific civilization has grown up from the material technique and social institutions of the distant past, in other words from the trades and customs of our ancestors. To find out about those trades and customs is the

task of the historians and their colleagues—the archæologists, anthropologists, and philologists. They must work from the material and written records of the past and from the analysis of the present customs and languages of primitive and civilized peoples.

Now in these early periods the facts are fragmentary, imperfectly known, and difficult to put together. Most are only accessible to experts in specialized fields who have usually been concerned with establishing the correct sequences and interactions of cultures and have rarely concerned themselves with the problems of seeking out the origins and influences of the sciences. Because I am neither a historian nor a scholar but a working scientist, my reconstructions are bound to be provisional and very open to criticism. It is however from such criticism, and from the research to which it should lead, that a coherent and reasonable picture can be built up.

It would, of course, have been possible to leave out entirely a discussion of the earliest periods. A perfectly intelligible account of modern if not medieval science could be written without it. But to do so would be deceptive. So much would be taken for granted, as either self-evident or arbitrary, which was in fact the result of specific scientific and social factors operating in antiquity. For example, the great debate about the revolution of the heavenly spheres that marked the beginning of modern science is unintelligible without a knowledge of the mythological cosmological origin of these spheres, which reaches at least as far back as the earliest stages of Mesopotamian culture (p. 83).

In this section I will attempt to give in outline an account of the first creation and differentiation of science in relation to the early developments of human societies. The range of history covered falls into two major stages divided by the critical invention of agriculture. The first stage covers the period of the Old Stone Age (palæolithic), Lower and Upper, based on food-gathering and hunting. The second stage covers the periods of primitive village agriculture (neolithic); that of the first city and river culture in Egypt, Mesopotamia, India, and China (the age of bronze); and lastly that of the independent cities based on trade (the age of iron), including the classical civilizations of Greece and Rome. It is convenient for the purposes of this book to separate out this last period, partly because it is so much better known to us from written sources,

but even more because its tradition passed directly into that of modern science. Accordingly Part II will be divided into three chapters: Palæolithic, Chapter 2; Neolithic and Bronze Age, Chapter 3; Iron Age and Classical, Chapter 4.

In each of these periods men made their contribution to the techniques and ideas which are the necessary basis of science. In the palæolithic were produced all the major ways of handling and shaping materials, including the use of fire, the practical knowledge of the occurrence and habits of animals and plants in wild Nature, as well as the basic social inventions of kinship, language, ritual, music, and painting. The village culture of the neolithic gave, besides agriculture, weaving, and pottery, the social inventions of pictorial symbolism and organized religion. The Bronze Age added metals, architecture, the wheel, and other mechanical devices; of even greater importance, it produced the crucial social invention of the city itself—the *civis* of civilization, the *polis* of politics. It was the city that made the technical advances possible, and with them a whole complex of intellectual, economic, and political inventions—those of numerals, writing, commerce, in the framework of a newly evolved class system and organized government. Already a conscious science was arising and the distinguishable disciplines of astronomy, medicine, and chemistry acquired their first traditions.

The Iron Age did not cause a marked transformation in material technique, though it added glass and improved tools and machines. Its chief contribution was to extend civilization far and wide by the use of the cheap new metal—iron; but the social inventions of the alphabet, money, politics, and philosophy prepared the ground for the rapid development and extension of techniques and science. It was in this period that the Greeks assembled and developed, out of the technical experience of the older empires, the first fully rational science with a direct and unforgotten connection with our own. But the Classical period was also one of warfare and social conflict, slavery and oppression. Its final expression, the Roman Empire, gave little to science though much to public works and law. Owing to its inherent contradictions it gradually decayed politically and intellectually, and with its fall the science of classical antiquity went into eclipse though parallel branches in Persia, India, and China continued to flourish and to prepare the way for a new advance.

Chapter 2

EARLY HUMAN SOCIETIES: THE OLD STONE AGE

2.1—*THE ORIGINS OF SOCIETY*

To find the earliest origins of science we must look into the period before there was any effective separation between the technical and ideological aspects of human culture—into the very origin of humanity itself. Now the first and most fundamental way in which human beings differ from animals is that they form continuing societies with a material culture adding new scope to the capacities of naked bodies.

Such *societies* must have had—as distinct from animal herds—better methods of getting food and protection than could be achieved by isolated individuals, and means of preserving and handing on these methods in the form of a continuous tradition. Already in their evolution from ape-like creatures, primitive men had inherited the essential bodily and mental equipment for *seeing, grasping,* and *handling* objects. In addition, they must have had from the outset a quite exceptional capacity for *learning* derived from a more *generalized* pattern of getting their living than most large mammals with specialized bodies and habits. It was this combined hand–eye capacity with an ability to learn [2.16] that made the use of implements possible; first the casually picked-up stone or branch, then one deliberately selected and shaped for the job. But as long as such advances were confined to individuals, however gifted, it could not constitute a full humanity. For any implement to be available to all and capable of progressive improvement, its making and use must be *taught* and *learned.* It must effectively be *standardized* by *tradition,* and that implies a continuing society.

The continuity of human societies was also made necessary and secured by the exceptionally long period during which the human infant is unable to fend for itself. This leads to a practically immortal family group through the association of different generations, particularly of the females. Grandmothers, mothers, and daughters ensure an unbroken human

tradition. That is fundamentally why in primitive societies the maintenance of the tribe depends on the women. As kinship is reckoned through the mothers, such societies are called *matrilinear*. A matrilinear stage seems to have occurred in all societies, including those of our ancestors.[2.46] It may even be that at a very early stage the women directed the affairs of the group, so that the societies were also *matriarchal*.

Now the methods which gave human societies their particular advantages were largely dependent on the use of material *implements* for catching, collecting, transporting, and preparing food, and also on a rapid means of communication to ensure co-operation in these tasks—in other words, on *language*. Through the use of implements man achieves a far greater and more generalized control over his environment than the animal most lavishly endowed with teeth or horns. Language, by gesture and voice, in addition to indicating the most effective use of implements, ensures both the coherence of society and the handing on of its accumulated culture to later generations.

2.2—*THE MATERIAL BASIS OF PRIMITIVE LIFE*

Implements and tools

Implements are essentially an extension of human limbs—the extension of the fist and tooth with the stone; the arm with the stick; the hand or mouth with the bag or basket; or an altogether new type of extension, by projection from the body, as when a stone is thrown with aim. The social control already necessary for the mere selection and use of implements became even more so when such raw implements came to be deliberately fashioned for their purpose. Every kind of instrument thus comes to be socially determined in its use, its form, and its mode of preparation.

The continuity of tradition in primitive life is shown, right from the beginning of the archæological record, by the actual objects made by primitive man himself. Even if we knew nothing about them from their use by contemporary savage societies, they would still bear evidence of their social origin. The implements of each type are practically identical in any given culture or area and do not vary much over very long periods and very large areas indeed. Now even the simplest of stone hand-axes has to be shaped by a fairly elaborate process of chipping, a process that would take civilized man quite a

long time to learn. The fact that this shape is preserved shows the extreme stability of technical tradition. In other words the actual shaping of a flint implement is itself an institutional cultural activity which has to be learnt and executed with the greatest care in order to secure the degree of uniformity which we observe.[2.36.78]

The uniformity is not, however, absolute. There are inevitable changes: improvements, borrowings, and combinations which have led, through a stage-by-stage evolution, to our present state of technique. But the important point is that through social conditioning man is able to have at his disposal at every stage of culture a reproducible, practically a standard, set of implements. Each tribal group, according to the way it gets its living, has a particular set, but many of these are common over vast areas. The habit of forming such standard sets, beginning in the early stages of primitive man, has been the major factor in preserving the absolute continuity of technical culture right down to our own time.

There is a further implication in the existence of standardized implements, namely the presence of the *idea* of an implement in the mind of the maker before setting out to make it. More than this, some partly worked flints show a definite blocking out of the material before the work is started. Later this experience of conscious foresight is to become that of *design* and *plan*, and hence of that characteristic of science—the *experimental* method. This comes from trying out various methods of making an object on models or drawings rather than always relying on full-scale trial and error.

If an implement, such as a stone picked up and thrown, is the beginning of human technical progress, that progress becomes unlimited once the *tool* is developed. The tool—the implement to make implements—creates the possibility of producing far more different types of implements than could be simply selected or snatched from Nature. The process of making tools, first by chipping from stone, then by grinding, and finally from metal by hammering and casting, underlies all our modern techniques of dealing physically with material objects. The first stone hand-tools simply smashed what they hit; later they were developed to split, cut, scrape, and pierce.[2.30a] Through the practice of tool making and tool using, men learned the mechanical properties of many natural products, and thus laid the basis of *physical* science. The use of tools not only made for

far more efficient hunting; it also provided a means of shaping and preparing softer materials—wood, bone, and skin. At the same time man, or more probably woman, was beginning to put things together—pinning, sewing, tying, twisting, twining, and weaving. In this way containers for food, water, and portable objects were evolved.

Clothing

Partly from the need to carry things about, at first only food and implements, came the custom of attaching objects more or less permanently to the body wherever a convenient hold could be made, in the hair, round the neck, waist, wrists, and ankles. These attachments tended to become distinctive and ornamental. Feathers, bones, and skins were added. Then came the crucial discovery that furry skins helped to keep people warm in cold nights and in winter. From this came *clothes*, first in isolated skin cloaks and skirts, then sewn and tailored garments, complete body containers, such as the Eskimos make today. These, together with skin foot protectors, enormously increased the range in area and in season of primitive man. So also, though in a lesser degree till settled agriculture came in, did wind-breaks, shelters of branches and leaves from which were to come huts and houses.

Fire and cookery

Almost every one of the early mechanical achievements of man, even to weaving and tailoring, had already been anticipated by specialized species of animals, birds, or even insects. However, one invention, the use of *fire*, which must have come earlier than many of these, is altogether beyond the reach of any animal. How man came across fire, and why he dared to tame and feed it, is yet to be discovered. Wild fire is either confined to special localities, as in the neighbourhood of volcanoes or outlets of natural gas, or occurs very rarely, as with forest fires. Its preservation and propagation must at first have been a very frightening, hazardous, and difficult thing, as witness the universality of fire myths and legends. At first it must have been used to warm the body on cold nights—the Australian natives carry round fire-sticks which are used instead of clothes in cold weather—and to frighten animals. Cooking could only have come once the camp fire had become an established custom.

The tool-using and fire-using animal is well on the way to a scientific humanity. Just as the tool is the basis of physical and mechanical science, so is fire the basis of chemical science. First of all came the very simple and essentially chemical practice of *cooking*. It is from this apparently almost accidental use of fire that the more specifically controllable and scientific uses of fire in pottery and later in metal-making first arose. It is not very difficult to roast meat on sticks, or even to bake roots in ashes, but boiling represents a real problem, the solution of which was to lead to further great advances. The first ingenious idea was to heat water in leather buckets or water-proofed baskets by dropping in hot stones. Such stones, cracked by heating and chilling, have been found round prehistoric camp sites. The crucial discovery, however, was that by coating a basket with thick clay it could be put on the fire and actually improved in the process. In time it was discovered, probably towards the end of the Old Stone Age, that the basket could be dispensed with and clay pottery made that would hold water and stand fire. Boiling, however, still remained a luxury, pots were heavy and not easy to carry on hunting trips. Among the plains Indians of North America the term " boiled meat " is synonymous with a feast.

Further, once containers which could hold liquids for long periods were in use, the slower chemical changes of fermentation could be noted and used. From this new knowledge came, ultimately, the general idea of transforming materials by dipping or embedding them in reagents of which the first triumphs were the arts of the tanner and the dyer. Thus already in the Old Stone Age the set of practical recipes was built up from which rational *chemistry* was to arise.

Animal lore

The operative knowledge, however, and the use of tools and fire, is only one part, and possibly originally a rather small part, of the specific human use of accumulated and transmitted experience. Earlier, and more immediately important, was the observational knowledge of Nature, not Nature in any general sense but Nature as it appealed to man's immediate needs, principally to his need of food. The knowledge thus obtained of the habits of animals and the properties of plants formed the basis of our *biological* science of today. A very large part of the interest of primitive man must have been directed to the collec-

tion and transmission of information on plants and animals. Animals, because of their movements and of the excitement and danger of hunting them, attracted the greatest interest.

Primitive art

For this, we have the evidence of the most detailed knowledge of Nature possessed today by all tribes still in the hunting phase and by the large part that animal dances play in their ceremonies. That this was also true in the past is shown by widely dispersed cave paintings, drawings, and sculpture, which are almost exclusively of animals. These representations do not stop at the outside of the animal, often bones, heart, and entrails are also shown giving evidence of the origin of *anatomy* arising from the cutting up of game. Indeed it is to this biological aspect of primitive life that we owe the techniques of pictorial representation, which are not only the fountain of the visual arts, but also of the graphic symbolism, mathematics, and writing, which have made rational science possible.

2.3—*THE SOCIAL BASIS OF PRIMITIVE LIFE*

Language

Long before such elaboration was possible, human society was evolving language, its most powerful means of cohesion and development. Language is itself a means of production, possibly the first of all. The co-operation of several individuals in the pursuit of game with their bare hands or with unshaped sticks and stones is possible only by the use of *gesture* or *words*. This may well have happened long before any instruments had been shaped for their purpose. Early language must have dealt mainly with the getting of food, including the movements of people and the making and using of implements.*

How early the acquisition of language must be is shown by the degree to which it has already influenced the inherited anatomical structure of the human brain. The complex of eye and hand co-ordination which occupies well over half the human brain is essentially only an elaboration of that inherited from an ape-like ancestor. The corresponding complex of ear and tongue co-ordination on the other hand, though not so large, is practically a new creation. It can only have arisen and have implanted itself in human heredity after the origin of society.

All mammals use their voices to some degree for social

communication, but usually for that of emotion—for sex, anger, or fear—and the hearing of these cries in turn generates an appropriate emotional response. It was only later that the communication of emotion and action could add the communication of information about things and places. The transition is not complete, the undertone of emotion in language comes to the surface in poetry, song, and music, but it is never absent from spoken language and gives it a moving and even compulsive character which has contributed to the belief in the *magic* of words. Yet the magical aspect of language has always been subordinate to the utilitarian one (*n.* p. 16).[2.45]

Language must have been, from the very beginning, almost entirely arbitrary and conventional. In each separate community the meaning of sounds had to win acceptance and be fixed by tradition into a complete language capable of dealing with the totality of material and social life. For the same reason languages are as diverse as language is universal.

Symbolism

The objects and situations which language is used to deal with are always far more complex than the sounds used to describe them. As a consequence the words of a language are necessarily *abstract* and generalized *symbols*. They are sufficient, and no more, to indicate the conventional action that the situation demands. In the very act of creating their languages human societies are forced to generalize, to let one word stand for many different things and to use a verbal symbolism or shorthand. The manipulation of these symbols in the brain together with direct visual *imagination* constitutes human *thought*. The *formulæ* and *theories* of science are only natural and guarded extensions of the process of framing a language. Verbal symbolism, as we shall see, can be the source of error as well as of knowledge. If the emphasis is laid on the compulsive emotive aspects of words, they can become magic *spells*. If the symbol is taken for the material object or action, they may be the counters of idealist *logic*.

Early social life

Language, for all its variety and capacity to change, has a permanency far greater than that of technique. The Stone Age is over and done with, but the languages we use today are basically those that must have been spoken by some stone age

tribes. So the study of language—a living relic of the past—should be an essential supplement to the study of the surviving relics of material cultures.[2.45; 2.46] Both, together with evidence from existing primitive people, should be able to provide some picture of the social life of early times. This is not the place—nor am I the person—to attempt such a picture, but only to indicate those parts that are relevant to the origin and influence of science.

The relations of the members of a social group to each other must from the outset have profoundly modified the activity and feelings of individual men and women. The finding of food, its preparation and sharing out, the very eating of it in set and often ceremonial meals, were all social acts. They were specifically human because they mark a profound change from the unconditioned animal reaction to food—always eating it when hungry and keeping others away from it. Man's reactions on the other hand are highly conditioned through the traditional customs set up for the maintenance of the social group. To put it in another way, *man is the only fully self-training animal.* In contrast to other mammals, where instinctive training is carried out by parents for the first few days or weeks of life, every human being who comes into the world is put through an elaborate process of education, beginning at birth and lasting for many years. The process of social conditioning or *education* is strictly traditional, and the tradition has maintained its continuity and changed very slowly from the beginning of society till this day (p. 705).

Food-gathering and hunting. The division of labour

Now the general ecological character of the human groups was determined at first almost exclusively, later very largely, by how they got their food. To begin with, they must have collected anything they could eat—seeds, nuts, fruit, roots, honey, insects, and any small animals that could be caught with the bare hands. We know nothing, except by inference, of life at this stage. All primitive peoples still surviving have passed into the next stage, where food-gathering is supplemented by hunting large animals. From the implements left behind it is possible to follow the increasingly elaborate techniques of hunting adapted for every kind of big game up to the mammoth itself.

The one unbridgeable social division carried over from the

animal stage is that between the sexes. The necessarily small social groups of the early Stone Age maintained their continuity through the women, while the young men for the most part must have gone off and mated with girls from other groups to which they then attached themselves. This corresponded to an economic division in which the women collected fruits, nuts, grains, and grubbed up roots and insects, while men caught small game and fish. At that level there was little to choose between them as food-getters.

The further development of big-game hunting—a man's business—increased man's importance as a prime food-getter. It may be that this, combined with the extra strength, aggressiveness, and skill that went with it, led towards the end of the Stone Age to the dominance of men over women, such as they have for instance among the Australian hunters. Families tended to become *patrilinear* and tribal customs *patriarchal.* This trend may well have been reversed when hoe agriculture came in, enhancing the woman's importance.

Totemism and magic

The very existence of the group depended on the daily collection of food, and this in turn depended on the supply of animals and plants living within the workable collecting range of a few miles, and on the ability of men and women to catch or collect it. Now only the latter depended on technique, and this necessarily changed very slowly. The numbers of animals and plants, on the other hand, varied widely and sometimes catastrophically. Man was entirely parasitic on uncontrolled Nature; what he could do by better techniques was only to deepen and widen the extent of his parasitism. He could not escape from it in reality till the invention of agriculture. Nevertheless he thought he could persuade and fool Nature to help him by methods which worked with his fellow tribesmen and with the animals he hunted. *Magic* was evolved to fill in the gaps left by the limitations of technique. By making each useful animal or plant the totem of a particular tribe or section of a tribe, by the use of images, symbols, and imitative dances, the primitive tribesmen believed that the animal or plant could be encouraged to flourish and multiply. This also led to food exchanges between different totem groups. Thus the elaborate social rules for relationships and for the sharing of food and ornaments could be linked together in one complex system.

As long as the rules of the totems were strictly followed the reproduction of the tribe and of its food supply would be secure. Linked to the totem is the ascription of powers to certain persons, animals, or objects; they are *taboo*, *sacred*; they can only be handled in accordance with the strictest rules whose infringement brings frightful penalties. The concept of an object with latent *mana*, power, or virtue has underlain, sometimes fruitfully, the development of science. For example, the fascination of the magnet, with its virtue of attracting iron, created the science of *magnetism*. Most often, as the virtues were imaginary, the worship of objects has prevented clear thinking, as with the importance given to that peculiarly useless metal —*gold*.

The totemic system is still in operation among many primitive peoples today. Traces of it are to be found in all civilizations, including our own, especially in the most conservative spheres of religion and language. Indeed, as Thomson has shown,[2.46] the whole of our terms of relationship—father, sister, uncle, etc.—are only to be understood in terms of totemic relationships. We still preserve in our lions and unicorns the relics of the totem animals transmitted through heraldry.

Ritual and myth

More immediately relevant to science are the *rituals* concerned with totem ceremonies, particularly those of birth, initiation, and burial.* That initiation rites were practised in the Old Stone Age is shown by the finding in caves of the indentations made in the soft clay by the participants of such rites and also by prints of mutilated hands. These rites, through which everyone had to pass, were accompanied with hymns expressing explanations or *myths* of the origin and development of the world in totem terms. This was the first formal *education*, that is the inculcation of a set of explicit beliefs about the world and how to control it, which completed, though it never took the place of, the practical apprenticeship of the actual techniques of hunting, cookery, etc. One of the features of initiation ceremonies was the giving of *names* which, because they implied the relation of the candidate to the totem ancestors and consequently to the whole world, were considered of special importance and sanctity. Indeed, as etymology shows (nomen—name = *gnosco*—to *know*), knowledge of names was the first explicit *knowledge*.[2.46]

All myths in their first formulation must reflect the level of practical technique and social organization of their period, but, because of their association with rituals deemed necessary for the preservation of the life of the tribe and indeed of the universe, they change more slowly than the change of conditions and often become unintelligible till re-interpreted in more up-to-date terms. The myth of the Garden of Eden, for instance, originally reflected the change from hunting to agriculture, but it has been used to cover the ideas of taboo, of sex, of the wickedness of knowledge, of blind obedience to God, and of original sin. Myths, even from different tribes, blend easily and go to form a somewhat incoherent common *mythology*. It is from such totemic myths, after many changes but with an unbroken continuity of tradition, that not only the *creeds* of the religions, but also the *theories* of science have come down to us.

2.4—*THE ORIGINS OF RATIONAL SCIENCE*

The different kinds of knowledge acquired by primitive man —those from implements and tools, from fire, from animals and plants, and from the rituals and myths of society—were not, at their first winning, at all distinct. Wherever they existed they blended into one common *culture*. To understand the genesis of science out of such a culture it is not sufficient to describe its development in terms of the experience of the men of those times. It is also necessary to examine it in the light of modern science. We have to assess the range of what was known at any period and in any field of experience in comparison with the relative complexity of what there is to know. A fully *rational* and usable science can arise only where there is some hope of understanding enough of the inner workings of a part of the environment to be able to manipulate it at will to human advantage. Now objectively, the inanimate world is simpler than the animate and much simpler than the social, so that it was intrinsically necessary that the rational and ultimately the scientific control of the environment should follow that order.

By making and using implements, man was transforming Nature according to his deliberate will. This was the origin of rational *mechanics*—the laws of the movement of matter in bulk expressed in the practical handling of the trap, the bow, the boomerang, and the bolas. Even without such an understanding of the workings of Nature it was still possible for man

to take advantage of any portion of the environment in which there was any sign of regularity. It was only necessary for man to know what to expect, without any need to bring things about himself, and to be there to take what Nature gave. This is the field of the *observational* and *descriptive* sciences, such as are the basis of the arts of hunting and of gathering fruits in their season. Beyond what might be controlled by direct human action and what might be expected from Nature, man still strove to exert his power, but by other means, at first magically, later in terms of religion.

The interests of primitive man were in any case severely limited and practical. They were confined to the provision of the necessities of life—food, animals, and plants—and the materials for tools and equipment, together with other things, such as heavenly bodies or features of the landscape, deemed to have something to do with their abundance. If the area of the rational and the expected was small, it was still a very large part of what actually interested primitive man. As society has developed, the area of effective science has enormously increased, but the field of interest has grown as fast or even faster. There is no reason to believe that primitive man felt any less secure in his world than we do in ours.

Mechanics

The beginning of the *rational* field is built into the structure of the physical universe and of the sensory–motor mechanism that had been evolved by animals in the course of thousands of millions of years in such a way that at each stage they make the best use of it. In the first place it derives directly from the visual–manual elements in the human body itself—the inherited eye–hand co-ordinations that gave man such advantage over other mammals, especially when he became a social animal. To put it another way, the possibility of rational thought for man begins in his relation to his *physical* environment. With a very simple device like a lever, for example, it is possible to know in advance what is going to happen at one end when you move the other. It was on the basis of this eye–hand co-ordination that the rational science of mechanics first grew up. It was in this field, and in the first place this field alone, that it was possible to *see* and *feel* intuitively how things worked. This was enormously reinforced by the knowledge acquired in early techniques. The roots of statics and dynamics are to be

found in the shaping, making, and using of implements. Thus it was that, long before any other science could exist, man had already achieved an inner and essentially mathematical logic in the physical handling of definite and discrete objects. As science advanced it was this physical aspect that always retained the lead in rationality over other aspects of science.

Classification in primitive science

It was only later, many thousands of years later, that the same physical methods could be used to deal with other aspects of human experience—the chemical and biological—and to make them as logically understandable and controllable. This does not mean, however, that the foundations of the biological and social sciences were not laid at this time, but only that they necessarily, from their very inner complexity, had to follow a different course. It was impossible to *see*, in the same rational way, what would happen as a consequence of any action in cookery or brewing. But it was possible to *know* what would happen first by trying and then by remembering or being taught. In this field, and even more in that of animal behaviour, knowledge was essentially traditional. It was then also strictly irrational because it was impossible with existing knowledge to understand and see the reasons *why* things happened. It did not, however, necessarily *seem* irrational, because the very familiarity of the experience made explanation unnecessary. In any case some mythical explanation could always be found, often in terms of abstract but personified operators like totem ancestors or spirits. The distinction between the rational and the descriptive fields was therefore never absolute. Further, there were plenty of likenesses and comparisons which could be made; whole classes of phenomena were roughly similar. It was in fact in this field that the practice of classification appeared which led to the development of the biological and to some extent the chemical sciences. These first classifications were necessarily embodied in language, which contains implicitly a theory of beings or things (nouns) capable of actions or passions (verbs). Here also arose a kind of descriptive reasoning by analogy, most often based on magic, which, though false at the outset, became more and more sure with the accumulation and sifting of experienced facts. Judging from the testimony of present-day savages, primitive peoples must have made a fairly clear distinction between the fields of

experience in which they had reasonably good control over things; those in which they could make a good estimate as to what would happen; and those in which they had to rely on ritual and magic. Nevertheless the close interlinking of these aspects made for very stable cultures.

The sanctions of tradition

The extreme slowness of change, as is borne out by the archæological record, shows how closely early men clung to tradition in all fields. This was possible because they felt implicitly the unity of all their culture and the danger of straying from tradition in any part of it. How could they know that any failure to carry out the customary rituals and to say the magic words would not result in the sudden overturning of the whole order of Nature: that it would not cut off the sources of food or bring disease? It was safer not to vary anything unless circumstances made it absolutely impossible to maintain the old tradition.

2.5—*THE TRANSFORMATION OF THE ENVIRONMENT*

So far we have discussed the origins of science in primitive society only in an extremely generalized way, emphasizing how its necessary adaptive responses gave rise to an increasing and better-ordered *knowledge* of the material, biological, and human environment. But this is only one side of the picture. The other is the development and use of techniques by early man, themselves altering that environment and driving him on to further fundamental changes in the pattern of life. They did this in two ways.

In the first place each new technique enlarged the area of the usable or controllable environment. A new type of weapon, such as the bolas, for example, already fully developed in the Old Stone Age, made possible the hunting of fleet game in open plains. New equipment might have even more important consequences. Fur clothes, huts, and fire enabled early man to winter in the north. Such revolutionary technical changes enabled mankind to spread to new areas and to live in greater density in the old areas. In the second place the successful use of a new technique, such as burning a forest for clearance, would in the long run physically alter the environment itself and lead to new problems for which technical change offered

the only alternative to extinction. Other crises, often indistinguishable by primitive man from those due to his own activity, were produced by uncontrollable changes in the physical environment due primarily to climatic variations. Both required either movement away from old areas or the development of new techniques to deal with the new conditions. Whether technical changes developed from within the culture or were imposed on it by changes in external conditions, they certainly occurred. Further, as the archæological record shows, the changes were mainly progressive and gave greater control over a wider section of the environment.

Equipment at the end of the Old Stone Age

Already towards the end of the Old Stone Age the archæological record shows man equipped with a rich array of technical devices—huts, sewn fur garments, bags and buckets, canoes, hooks, and harpoons. It can be interpreted the more easily because most, if not all of these are found in active use among the present-day savages, notably the Eskimos, and in a more restricted way among the South African Bushmen and the Australian aborigines. Their technique was one limited to food-gathering and hunting. Not only was the major direction and aim of life turned to the pursuit of animals, but the equipment of the hunters was very largely made from the remains of the animals they had killed. It was on the basis of such a hunting economy that solutions were found to most of the mechanical and technical problems of shaping and joining material (Fig. 1).

It is interesting to note that although the materials have changed, most of the types of solution found at that time for these problems are still in use and are often still the main basis of modern techniques. For instance, one of the major early problems of civilization was to find means for preserving and carrying liquids about. The first buckets and bottles were of skin, and although the materials have changed, the methods of manufacture have merely been adapted to use sheet metal for buckets and cans. Even when glass and plastic have replaced leather, the essential shapes have remained the same. Basketry was certainly known in the Old Stone Age, as were crude weaving, probably derived from it,[2.49] and the plastic properties of clay. Further developments in that period of cloth and pottery were retarded not for any lack of technical ability, but

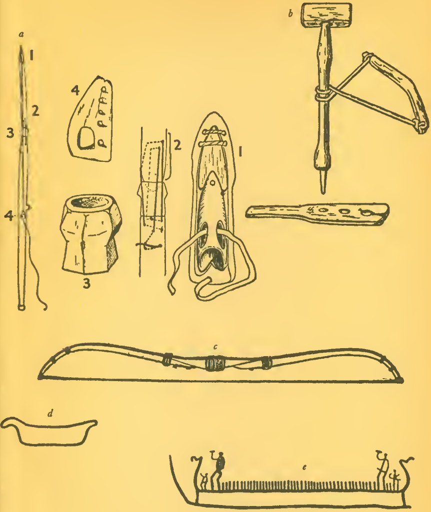


FIG. 1.—PRIMITIVE TECHNOLOGY

Eskimo Equipment

(*a*) Harpoon with detachable head (component parts shown enlarged).
(*b*) Bow drill.
(*c*) Composite bow.

Early Boats (drawn outlines from Norway)

(*d*) Stone age skin boat similar to Eskimo *umiak*.
(*e*) Bronze age boat—the strokes stand for crew.

because the conditions of nomadic hunting did not leave the women long enough in one place to carry out the complex operations of spinning, weaving, fulling, and dyeing, and at the same time there was little demand for goods such as clay pots, which were heavy to carry around (Fig. 2).

Missiles and machines

Particularly important for the history of science were the mechanical developments in hunting itself. The spear, the throwing-stick, the extremely ingenious boomerang, the sling, and the bolas, whose action depend on rather complicated dynamical and aero-dynamical movements of systems in space, are successive extensions of the simple art of throwing sticks and stones. More elaborate and far more significant for the future was the crucial invention of the bow, which seems to have occurred only in the latter part of the Old Stone Age. The bow represents the first utilization by man of mechanically stored energy, the energy stored up in bending the bow slowly in the draw being expended rapidly in loosing the arrow. The bow must be one of the first *machines* used by man, though the spring or fall trap makes use of similar principles, and may be even earlier. The bow must have led to far more efficient hunting, and its use seems to have spread very rapidly throughout the world (Fig. 1).

For the history of science, its interest is threefold. The study of the flight of the arrow stimulated *dynamics*. The bow drill, substituting the action of the hands—and liberating one of them—in twisting a fire-stick or a borer, was an early example of sustained *rotary* motion. The twang of the bow-string was the probable origin of stringed instruments and thus contributed to the *science* as well as the art of *music*. The other and probably earlier mode of producing musical sounds was from wind instruments, of which the horn and the pipe must go back to Old Stone Age times. Primitive man knew well enough from experience that air and wind were material. *Pneumatics* started with the breath. It could be directed by blowing or sucking through hollow bones or reeds. Air could be stored in bladders for floats, and pressed out of bellows for urging the fire. Its spring could be used in the *blow gun* for hunting or in the bamboo *air pump* for producing fire. This movement of a free or driven piston in a cylinder was to be the genesis of the cannon and the steam engine.

2.6—*SOCIAL ORGANIZATIONS AND IDEAS*

Naturally, because the records are material, we know far more of the technical achievements of primitive man than we do of his achievements in the realm of ideas; but the few indications that we have, combined with what we know of primitive races today, show that they must also have been very considerable. In the first place, it would be impossible to carry out the complex mechanical and organizational jobs of a hunting society without a considerable capacity for intercommunication and social organization. Hunting was often on a large scale, and of such animals as the mammoth or the wild horse, involving the skilful disposition of hundreds of men.

There is, moreover, direct evidence of the development of myths and rituals in palæolithic sites, particularly in burials. The very fact that burial was practised from almost the beginning of the Old Stone Age indicates an attitude towards the fate of man after death. The attitude seems a somewhat simple one; burials with implements and food are indications of belief in an after life not very different from that of contemporary religions. But certain practices, such as that of covering the corpses with red ochre to simulate blood, indicate a very considerable practice of magic. This is also borne out by all the remarkable paintings that lower palæolithic man has left us in caves and rock shelters (p. 43). These paintings themselves are of an essentially magical nature and are aimed mainly at providing better hunting and more animals to hunt.

It is fair to assume, on the analogy of present primitive tribes, that this evidence points to a whole complex of ritual, essentially composed of dances and songs re-enacting the success of the hunt with masked dancers representing the animals. It is from such ceremonies that the arts of the theatre as well as the rituals of religion must descend. The imitation of animals was of course for the purpose of *deceiving* them, and its success would not long be confined to animals. The deceptive actions would be transferred to war and the poetic fiction could easily degenerate into the plain lie.

The medicine man

At first all must have participated in ritual ceremonies, but towards the end of the Old Stone Age there is evidence of some beginning of specialization. The paintings in remote and

inaccessible caves must have been carried out by trained artists who must, moreover, have still participated enough in the chase to find and study their models in action. Among these paintings are occasionally found single figures of men dressed as animals who seem to have had some special importance. In most primitive tribes today we find medicine men or *shamans* who are thought to have peculiar relations with the forces deemed to control those parts of the universe or environment that matter—primarily food, but also health and personal luck. These people are, to some degree, set apart from the whole-time work of food and implement production, and in return they exercise their magical arts for the common good. They are also responsible for the conscious preservation of traditional learning and consequently for its modification in a developing society. Their forerunners in ancient times are therefore the lineal cultural ancestors of sacred kings, priests, philosophers, and scientists.*

The theory of magic: Spirits

The operations of the magicians were based, probably at first only unconsciously but afterwards explicitly, on an essentially imitative and sympathetic kind of theory of the working of the universe. From the evidence of the burials and pictures it would seem that this was already elaborated in the Old Stone Age. First likenesses and then simplified *images* or *symbols* could be so identified with the originals that operations on them were transferable by sympathy to the real world. An unbroken sequence links those images and symbols to those we use with such success in modern science, but centuries of experience and bitter struggles were necessary to distinguish the magical from the merely conventional value of symbolism.

Another aspect of primitive thought which at some stage split off from imitative or symbolic magic was the idea of the influence exerted in the real world by *spirits*, and consequently the need to control or propitiate them. The idea of a spirit is in itself a highly sophisticated one. It probably originated from the inability to accept the fact of death; and early spirits, as the grave furnishings show, were conceived as very corporeal indeed. But because they had been members of the tribe when alive they were deemed to continue their concern with it. They were thought to work on Nature as live men did by direct action or by magic, and originally their power was no

greater. It was only later that the spirit (breath, geist, soul, psyche)—that which left the body at death—was imagined as separate from the body and capable of an invisible but not ineffective life of its own.

Ultimately, the conception of spirit was to split into two very different ones. The first was the transformation of the spirit of a powerful man through that of a legendary *hero* into that of a *god*,[2.42; 2.46] to become the central figure in *religion*. The second was the divorce of the spirit from its human origin into an invisible natural agent such as the wind or the presumed active force behind chemical and vital changes. The latter, purged of its divine nature as will be shown in subsequent chapters, played an enormously important role in science, ending up when condensed as the "spirits" of the gin-shop, or remaining as the "wild untameable spirits"—the gas (or chaos) of van Helmont (p. 447)—that were ultimately to pass into the confinement of the gasometer.

2.7—*THE ACHIEVEMENT OF PRIMITIVE MAN*

This all-too-brief survey of the techniques and ideas of primitive man should at least suffice to show how much had already been done by the end of the Old Stone Age in using human intelligence to control Nature by material instruments, and, through the workings of society in tradition and ritual, to ensure that the advances gained should be retained. The basis of *mechanics* and *physics* had been established in the making and use of implements, the basis of *chemistry* in the use of fire, and that of *biology* in the practical and transmissible knowledge of animals and plants. Social knowledge was implicit in language and the arts, and had been systematized in totemism with the beginning of formal education in initiation ceremonies.

The character of the society, determined by its dependence on hunting and food-gathering, was essentially communal, without any marked specialization and without class divisions.

The limitations of a hunting economy

The excellence of the technical and social achievements of palæolithic men was such that one may wonder why they were not able to maintain themselves indefinitely in that state. Indeed, some have apparently done so, but only in the most

outlying places, such as the Arctic and central Australia, or in the tropical forests. It is still, however, doubtful how far these are really palæolithic survivals or merely neolithic groups pushed back by especially hard external conditions on to a secondary palæolithic hunting and food-gathering culture. For the rest, palæolithic technique was perhaps too well adapted to its main purpose of hunting a limited number of species of game in a limited number of habitats, particularly open plains. If the conditions determining their abundance were altered, either by climatic changes or by over-hunting by the tribesmen themselves, the herds would die off and the tribesmen would either have to move off to more favourable regions, die away on the spot, as many tribes did and are doing today, or learn to change their hunting culture for another—a far more difficult task.

The essential weakness of a hunting society is that it is parasitic on the animals it hunts. It is able to make the greatest use of the animals that are there, but not to control them in any positive way; that is, it can kill off the animals, but it cannot feed them or make them breed. In fact it was probably the very efficiency of late palæolithic techniques that caused the disappearance of large animals from wherever they could be easily hunted. Another contributory cause was changes of climate, which replaced the open happy hunting grounds by forests in some regions like western Europe or by deserts in others, as in Africa. Certainly hunting, about the period of the end of the Ice Age, ceased to be the most progressive type of human culture, and though its arts and even its social organization were preserved, they persisted only as a part of a far richer and more progressive culture brought about by the invention of agriculture.

There may also have been internal reasons rootcd in the form of palæolithic society that made it less able to cope with its environment, but it is still difficult to analyse them. Primitive societies of this level of material culture are rare today, and their purely internal difficulties are masked by the destructive influence of more advanced cultures, particularly our own.

Chapter 3
AGRICULTURE AND CIVILIZATION

3.1—*TOWARDS A PRODUCTIVE ECONOMY*

Agriculture

THIS chapter covers the periods usually known as the neolithic or New Stone Age and also the Bronze Age—the period of the early river civilizations of Egypt, Mesopotamia, India, and China. No attempt will be made to trace the histories of these civilizations, but only to bring out the part they played in the origins of science.

About 8,000 years ago there began a revolution in food production that was to alter the whole material and social mode of existence of man. This was mainly, if not altogether, a result of the crisis in hunting economy discussed at the end of the previous chapter. The difficulties that men had to face at that time led to an intensive search for new or even old and despised kinds of food, such as roots and the seeds of wild grasses. This pursuit was to lead to the invention of the technique of *agriculture*, ranking with the utilization of *fire* and of *power* as one of the three most momentous inventions in human history. Like all great transformations it was not a single act, but a step-by-step accumulation of interlocked inventions all subservient to the essential achievement—the cultivation of seed-giving grasses. In essence this was a transformation of society from the exploitation of the animate environment to its control, the first step in the achievement of a fully productive economy.

The origin of agriculture

The precise origin of agriculture is and will probably long remain conjectural. The limitation of the plants and animals used in agriculture to a very few closely related kinds—edible seed grasses, horned cattle—points to it having arisen in a definite period in some limited area, probably in the Middle East. It is not even certain whether the growing of crops and the domestication of animals were always associated or were the result of the coming together of purely agricultural and purely

pastoral cultures. The evidence [2.11.75] seems to point to the former alternative. Originally animals may have been attracted by the extra fodder left by the grain-growers and tamed. Domestication was not absolutely new: already in the Old Stone Age the dog had been tamed. One small clue that has struck me is that the almost universal means of cutting grain—the *sickle*—is clearly, from its shape and the teeth with which it was originally furnished, a substitute for the jaw of a sheep or other ruminant which is a very effective grass-cutter.* It would hardly have been used, however, if sheep had not been fairly plentiful and presumably tameable in the very first stages of agriculture. The growing of crops is in any case a more far-reaching invention than the domestication of animals, for without supplies of fodder it is usually impossible to keep an adequate number of animals in a restricted area. Further, the market for meat, skins, and wool provided by the townsmen is essential to an extensive pastoral economy. A nomadic tribe of shepherds or cattle-men on the open ranges needs as much land as if it were hunting the same animals wild, while without a market from which weapons, ornaments, and supplementary food can be got there would be little incentive to exchange the excitement of hunting animals for the trouble of herding them.

The cultivation of grain may, however, have arisen without any violent break in culture in a well-stocked region where wild grain was abundant enough to be plucked by the women and kept in baskets in permanent settlements.† Enough seeds would get scattered around to produce crops worth reaping. The *invention* of agriculture is probably little more than a sufficiently clear understanding of this accidental occurrence to justify the practice of sowing grain as a *deliberate sacrifice* of good food, for a more ample return in the next season. This implies a certain fixity of settlement which may have been determined in any case by the limitation of open land in a forest, or watered land in a desert. There is some evidence that agriculture may have started on the alluvial fans of mountain streams on the edge of desert plains, which would be a natural point of retreat for game and men as the plains dried out.

As grain-gathering was women's business, agriculture was probably a women's *invention*, and in any case was women's work, at least till the invention of the ox-drawn hoe or plough, for it was done with the *hoe*, a derivative of the old stone

age *digging stick* with which women used to grub for roots. Where agriculture predominated over hunting in providing food it accordingly raised the status of women and halted and reversed the tendency to change the reckoning of descent through the mother (*matrilinear*), to that through the father (*patrilinear*), which hunting had first induced. Only where stock-raising predominated, as in the lands bordering the agricultural settlements, was there a complete transition to the patriarchy—as we see it in the Bible.

Whatever its origin, agriculture led to an essentially new relation between man and Nature. Man ceased to be parasitic on animals and plants once he could grow in a small area as much food as he could hunt or collect over a wide range of country. In practising agriculture he *controlled* animate Nature through a knowledge of its laws of reproduction, and thus achieved a new and far greater independence of external conditions. The first agriculture may well have been a mere scratching of the ground, or garden culture, carried out in patches temporarily cleared and then abandoned, a kind of nomadic agriculture which is still practised by many tribes today. But even at this low level the practice of agriculture had an explosive effect on human material and social culture. Compared with any of the changes that occurred in the Old Stone Age, it marked a new order of advance. It led to a new kind of society which was *qualitatively* different, because of the enormous *quantitative* increase in the number of people that could be supported on the same land. Hunting had to be a fairly continuous occupation, but agriculture depended on the seasons. Most of the population could be set free for other tasks for some part of the year. Thus agriculture brought new possibilities and with them new problems.

Crafts of the field and the home

Agriculture itself involved a set of new techniques in the growing of crops and the preparing of food from them, such as sowing, hoeing, reaping, threshing, storing, grinding, baking, and brewing. With them came a whole set of ancillary techniques, either, like weaving, made possible by ample supplies of wool and flax, or, like pottery and hut-building, arising from the possibilities and needs of permanent occupation. Hut-building was known in the Old Stone Age, but only in localities where there was enough game to allow of permanent settlement. In

agricultural communities it was universal. Everything conspired to put a new tempo into cultural development. The need and the material means were there. The tyranny of old customs had to yield to new conditions. One new factor was the emergence of real property, though first of *communal* and not of *private* property. In hunting communities most of what was produced was consumed on the spot, and the only permanent goods—hunting gear, cooking utensils, and clothes—were in constant and largely personal use. In an agricultural community, on the other hand, land, cattle, huts, and stores of grain were always there as more or less fixed *goods*, largely communally held, and means had to be found of safeguarding and distributing them. At first this was done by extending and further complicating the totemic group organization. The rule was share and share alike inside each group, and ritual exchanges, minutely regulated by custom, were made between groups on ceremonial occasions such as weddings and funerals. But the new methods of production were in the end to be too much for the old system of distribution. Barter began to take the place of ritual exchange, individuals began to stress their claims to what they had produced, and *private property*, with its inevitable consequence of *inequalities in wealth*, came into being. The next stage—the formation of *social classes*—does not, however, seem to have developed until the founding of cities.

Work

Agriculture also introduced a new concept into social life: the concept of *work*. In the days of a hunting culture, work was not conceived as distinct from other aspects of life. Actions were closely related to their consequences. You hunted for food which you and yours were going to eat fairly soon. But in agriculture there was a long interval between what you did and what you got for it, and at the same time many of its operations were tedious and exhausting in themselves and lacked the excitement of hunting. True, the food supply was more secure, but the possibilities of wonderful hunts and great feasts were lost. In fact the transition from hunting to agriculture was a transition which we now know in our legends as "the fall of man." Man left "paradise" or "eden," which means the plain or happy hunting ground, to take up working for his bread by the sweat of his brow.

Science and the new crafts

Nevertheless, the very indirect relation of work to its reward that agriculture introduced led to a further extension of the concept of cause and effect which was to become the basis of a rational and conscious science. For example, the whole life-history of animals and plants now came under interested observation. It was necessary to know how they bred and grew, not only how to catch the one or gather the other. Similarly the new techniques that came in with agriculture introduced new mathematical and mechanical concepts. *Weaving* is clearly a further adaptation of basket-making, and both of them involve regularities, first of all actually practised and then thought about, which are at the basis of *geometry* and *arithmetic*.[2.49] The *forms* of *patterns* produced in weaving and the *number* of threads involved in producing them are essentially of a geometrical nature, leading to a deeper understanding of the relations between *form* and *number* (Fig. 2). *Spinning* was, with the possible exception of the bow drill, the first industrial operation involving *rotation* and may well in turn have led to the use of the wheel, which in the next period was to *revol*utionize mechanics, industry, and transport. *Pottery*-making, on the other hand, was the first indirect application of fire and demanded far greater control of it than did lighting, warming, and cooking. The use of pottery was in turn to extend the range of cooking operations and was to make the smelting of metals and early chemistry possible.

The neolithic age

The period between the first invention of agriculture and the founding of cities is usually known as the New Stone Age or neolithic age. It was so called because of the use of ground and polished stone implements in place of the chipped instruments of the Old Stone Age. In the centres of ancient civilization it lasted roughly from 5000 B.C. to 3000 B.C. The culture characterized by polished implements covers, however, a much longer period of time, and indeed there are many peoples in the world today living in a state of neolithic culture. It would appear that these existing neolithic cultures have arisen in two ways. Some may be in direct continuity with primitive neolithic culture which spread widely from the original centres in the Middle East; others may have derived from a much later spread of bronze age peoples who, moving into regions where

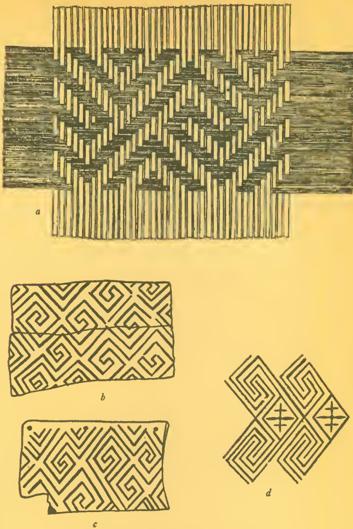


FIG. 2.—INFLUENCE OF BASKETRY TECHNIQUE ON DECORATIVE ART. (Pp. 52, 63)

(*a*) Piece of woven matting to show how Greek key design originates from simple alternations.

(*b*, *c*) Pieces of mammoth ivory of palæolithic date from near Kiev. Note mistakes and distortions.

(*d*) Design from the tomb of Thutmose III (c. 1500 B.C.).

From Weltfish.[2.40]

they were cut off from the products of their parent cities, lost all but their basic neolithic material culture and retained only certain bronze age ideas, such as sun-worship. The first megalithic long-barrow folk, who came to Britain 4,000 years ago, may have been such a group. So also may the Polynesians who spread over the Pacific during our Middle Ages.

The very persistence of neolithic culture over most of its area shows how in it man had achieved a new equilibrium, though now with the produce of soil and climate rather than as before with animals and plants in the state of Nature.

The formalization of religion

This transformation in the material basis of common life which came with the invention of agriculture was bound to have a profound effect on the mental sphere which was expressed in new rituals and myths. The chief concern of the neolithic community was with crops. Accordingly the woman's side of the totemic rituals for increase and reproduction of plants was emphasized and further developed. The most characteristic were *fertility* rites, in which human matings were used to encourage the crops. The influence of rain on vegetation, noticed in the days of hunting culture only indirectly through its effects on animal life, now became a matter of life and death. Imitative magic to produce rain became the other main object of ritual.

This concentration tended to make ritual and magic more orderly and to bring about their transformation into *government* and *religion*. Regular spring and harvest festivals were celebrated. Corn queens or kings and rain-makers were chosen and given special consideration and powers because they were regarded as essential to the life of the community. The need to bury or kill the grain before a new crop could grow led to the idea of *sacrifice*, even of a human sacrifice, in which the king himself or his representative was called on to die for the welfare of the people.

Village culture

The characteristic economic and cultural unit of the neolithic age is the *village*. Now many centuries must have been needed to evolve the complex interrelationships of technical and economic operations carried on in a village that ensures its practical independence in its own territory. Village economy,

however, is strictly limited in scope and possibility of change. Even where it involves thousands of people, as in some African villages today, it remains an economy in which nearly all the people are occupied most of the time in agricultural pursuits or in the production of locally made and locally used goods. The self-sufficiency of the neolithic village favoured its spread, but it hindered its further development.

3.2—*CIVILIZATION*

River culture

The first step towards a larger scale of operations occurred when people tried to practise agriculture in the wide alluvial valleys of such great rivers as were free from unclearable forest, that is, flowed in their lower courses through arid lands. They may have started from the low river banks, where seeds could be sown in the wet mud, as tribes in the Upper Nile still do, and then gradually cut back the marshes and cleared the river channels. Alternatively, the practice of agriculture in small upland valleys may simply have been pushed down-stream step by step into the great valleys. In either case there would be an incentive to canal cutting and embanking. In some such way a new kind of agriculture based first on natural, then on artificial irrigation came into being. In such a territory the village ceases to be the natural economic unit. Floods and droughts do not respect village boundaries; embankments have to be raised and canals have to be cut by many villages working together, and the distribution of the water must be fairly partitioned between them. When such co-operation, even that between half a dozen villages, was achieved or imposed the yield of the land of each of them increased. This marked another quantitative advance in food production, as it enabled a still larger number of people to live on the land, and this in turn led to a qualitative change in social organization.

Extension of social co-ordination

Social co-ordination over a far larger area than the simple village was in fact necessary to get the full value out of river-valley agriculture; but once it was achieved it was consolidated by its very success. Simply to increase the scale of an operation often leads to altogether unsuspected possibilities. When the tribes of the Nile villages federated, or were conquered so as to

form one economic unit, they were able almost at once to produce so much more surplus wealth that in the space of two or three centuries they were in a position to support the enormous economic burden of the State works of the first Egyptian empire.

Another example, from more recent times, shows how important is the effect of organization by itself without notable technical changes. The Inca empire of Peru arose out of the welding together of a number of independent tribes each cultivating its own bit of valley, arranging its own limited irrigation canals, and living off its own produce. The energetic and domineering tribe of the Incas, later to become a kind of sacred aristocracy, partly by political genius, partly by force, made these tribes federate. They thus made it possible to treat whole valleys as one unit, to drive long canals, to terrace whole mountain-sides, and to arrange for the suitable division and appropriation of food. As a result, for the centuries during which their empire lasted, no one in Peru needed to go hungry. Now the interesting thing is that this system, although it did not employ any new techniques, provided a surplus of products great enough to maintain the Inca ruling classes—the children of the sun—in very considerable splendour, and it also enabled them to create within a matter of a few centuries a quite high level of intellectual culture and a remarkable architecture.

Civilization could only have originated and first taken root in the well-watered river valleys, where cultivation by natural flow irrigation canals could be practised. Later it was to spread locally by the much heavier engineering works of lifting water for high-level channels, digging wells, and terracing hill-sides, but until the Iron Age it could never get far from the alluvial plains. Early civilizations were accordingly limited to a number of favoured areas, the main ones known to us being those of Mesopotamia, of Egypt, and of the Indus valleys, and, some centuries later, of the valleys of the Oxus and Yaxartes, the Yellow River, and the Yangtze.

The origin of the city

We are apt to think of *civilization* as arising primarily from the *city*—the *civitas*—which gives it its name. But the city was actually a consequence and not the cause of civilization. A city differs from a village by the fact that most of the inhabitants are not food producers working on the land, but administrators,

craftsmen, traders, and labourers. Before a city can be founded the level of technique of agriculture must be so raised that the non-producers in the city can be maintained on its surplus. As we have seen, such an agricultural technique requires at the outset some central organization. This implies a body of administrators covering a number of villages. One of these, containing the temple of the leading totem god, would naturally become the *city* where the surplus from the remaining villages would be collected and stored. As we do not yet know where the first cities were, the transition from village to city seems more abrupt than it probably was. Of existing cities Jericho seems the oldest, for there masonry walls are found in a period so early that pottery was not known.[8.35a] In lower Mesopotamia it is possible to trace a transition between villages and small cities built on the same site. Any later foundations of cities [2.46] are bound to have been influenced by the idea or even the experience of what a city should be like. Some evidence suggests that cities were founded by bringing together part or all of the populations of several villages. The site of the city itself may have been a strengthened natural hillock, a refuge against floods afterwards sanctified as a temple platform on which the temple stood like a mountain, the prototype of the tower of Babel.

A city may have arisen in the first place from the village of the chief water magician of the district, through whose instruction the irrigation was organized. This does not necessarily imply any great innovation or even much conscious use of science. The digging of canals and working of sluices need at first have been little more than clearing out existing water-courses and breaking holes in naturally formed banks, very much as in historic times the elaborate dike systems of Holland were evolved from sand-pits and mud-banks. Here, as in all beginnings, art (*technè*) follows Nature (*physe*) as Theophrastus says: ". . . it is manifest that Art imitates Nature, and sometimes produces very peculiar things." [2.44a,139] To succeed, however, without confusion, the work of irrigation would need some authoritative direction delegated or assumed with religious sanctions.

Once a city was established, however, a new division appeared: that between town and country. This did not happen all at once; for centuries most citizens owned and worked lands outside the walls. The surplus provided by the new efficiency of agriculture went to the city; not much was

left for the villagers to enjoy. The Egyptian peasant of early dynastic times was probably rather worse off than his ancestors in the neolithic age as regards freedom and conditions of work, though he had a better and more regular food supply. But he was no worse off on either count than his descendants, the modern fellahin.

The evolution of the house

At first the cities hardly differed from villages: just an assemblage of huts, each with a courtyard for animals, the dwelling-place of one family, but usually one of several generations, together with servants and slaves. As the population grew, more huts were added to the court, often as lean-tos inside the wall, making the first real houses. These came to be made of mud brick, as the danger of spreading fires from reed huts was too great. The life of the house centred round the court; the outer walls were windowless. In hot weather the family slept on the roof under an awning and later upper stories with windows appeared. The spaces between the houses gradually shrank into streets, though some were left for markets and the remainder for gardens. Round it all, as property grew and war threatened, was built a wall constricting and crowding it still more. When civil strife threatened as well, an inner fortress or citadel was built, from which armed men could dominate the city or into which they could retreat at need.

Temples, gods, and priests

The city was centred round a *temple* or big house, in which one god assisted by his priests superseded or ruled over a small pantheon of local village totem ancestors.

The institution of *gods* is essentially one derived from city life, and was brought about by the exaltation of the simple clan spirits through the newly available wealth. For that reason the god might well be an animal, as in Egypt, or have animal doubles like Zeus and his eagle. The first gods, as we meet them in Sumerian legends of 5,000 years ago, were very human indeed. They had their councils, quarrels and debates, very like an assembly of village elders.[2.20] In each city sooner or later one God and his consort usually came to dominate, but the others were not abolished but assigned subsidiary roles. At the same time the growth of cities was marked by the increasing

separation of the God from tribal and village concerns and His identification physically with His house in the city, and with the administration of His lands and property by His priests. From the beginning these priests ran the cities and drew the largest share of their benefits. They were the heirs of the medicine men of the Old Stone Age and of the magic kings of early agricultural communities, though in Egypt the magic king remained as Pharaoh, ruler and high priest. The *priests* formed the first administrative class, having definite and indeed essential functions; they arranged for the distribution of water and seed, for the timing of sowing and harvest, for storing of grain, and for collecting and apportioning the herds and their produce.*

Temple servants and craftsmen

The physical work needed to maintain the organization of the economy was not, however, done by the priests, or done only in a symbolic way. We see for instance pictures of the priest-kings of the ancient Sumerian cities carrying the first basket of earth from the excavation of a canal, and of Egyptian Pharaohs wielding a hoe, much in the same way as their successors today lay foundation stones. A body of temple servants was required for collecting, storing, and guarding the surplus produce. The temple itself became an establishment needing building and upkeep and the preparation of increasingly lavish ceremonials and feasts. The table of the god had to be well supplied. The exalted god naturally appreciated only the spiritual essence of the food, while the priests had to be content with its material remains. All these activities required workers who tended to become more specialized and gradually altogether removed from the work of agriculture. Builders and carpenters, potters and weavers, butchers, bakers, and brewers congregated round the temple and shared, though modestly, in its revenues. The first complete *division of labour* took place as these craftsmen were attached to their tasks and divorced from the land. Nothing could be too good for the gods, and, with supplies of materials assured from the agricultural surplus, the craftsmen rapidly improved their techniques. New crafts such as that of the jewellers and metal-workers were added to the old. In the cities the old clan organization of the villages, already overstrained by the appearance of property, was reduced to a formal role or continued as a guild mystery for the followers of particular crafts.[2.46.332]

Class-divided societies. Slaves and serfs

Up to the present little has been written on the original process of transformation of village into city economy. The evidence may be there, but it has not been fully interpreted. We badly need an economic and social analysis of the really primitive bronze age cities, similar to that which Thomson has given us of the iron age cities of Greece.[2.46] When the archæologist reveals them the earliest cities seem far along the road of *class-divided societies*, and early laws are quite explicit on the point. In the Code of Hammurabi (*c.* 1800 B.C.) for instance we find in a table of retributory penalties the following:

> If a man destroy the eye of another man they shall destroy his.
>
> If one break a man's bone they shall break his bone.
>
> If one destroy the eye of a freeman or break the bone of a freeman, he shall pay one mana of silver.
>
> If one destroy the eye of a man's slave or break a bone of a man's slave he shall pay half his price.[2.226]

This implies three grades. In most early cities we find citizens graded according to their wealth, including priests, merchants, and free craftsmen; there are domestic slaves and, outside the city, there are peasants who are virtually temple serfs.

We can only guess the early stages of differentiation of this class society, mostly on the basis of much later and more accessible evidence from Greece. It would appear to arise by a progressive modification of the *sharing out* of the produce of the village community, supervised by the priests, who managed to appropriate more and more on behalf of the god, and by the accession into the population of a number of disfranchised men and strangers, who had no right to any share at all.

Trade and merchants

The resulting inequalities were further accentuated and made permanent by *trade*, which itself arose out of ritual exchanges and later became a necessity. At first this was effected by simple barter, then by the use of cattle (*pecunia*) as units, or through valuable goods convenient for exchange because of their ready transportability, such as shells, gold, and silver, and finally by credit. The need for specialized traders arose originally out of the need for foreign goods necessitating journeys

or even armed expeditions. These *merchants*, originally city or royal officials, later set up on their own and came to live mainly by trade. At the outset the temple of the king was the chief storehouse and bank on which all economic life was centred. There taxes were collected in kind; from it distribution was made of food and raw materials. Most craftsmen were virtually serfs, receiving raw materials and food from their priestly or noble masters and handing over the finished goods, though even in early times there came to be some independent craftsmen who bought their raw materials and sold their wares. Propertyless men sold their labour for wages. Those in need borrowed; those with superfluity lent at exorbitant interest; those who could not pay were sold as slaves.

Law and the State

Laws had to be evolved to prevent these transactions leading to losses to the temple or to bloodshed. These laws are among the earliest written documents. In some of them we find everything regulated down to prices, wages, and doctors' fees. Thus in the Code of Hammurabi we find the fee for setting a bone or curing diseased bowels is five shekels for a man, three shekels for a freeman, and two shekels for a slave—the latter to be paid by the owner.

The force behind the laws could no longer, as in hunting or even village communities, merely be the traditional sense of what was permissible or taboo, or even the clan responsibility for the doings of any of its members, to be settled by a feud or composed by a ceremonial payment. For a city where there was social inequality an apparatus of force was required.

In the cities of Mesopotamia the original assembly of citizens, faced with threats of inner or outer violence, gave way to one-man rule either in the form of the *ensi* or chief temple administrator, or of the *lugal*, great war chief, but also priest of the god. In Egypt the divine priest-king, Pharaoh, was from the first dynasty head of the State. The laws were enforced and the taxes collected by a body of temple servants with police powers. The king also arrogated to himself the right of *punishment* by fine, imprisonment, beating, or death. The power of the State, though vested nominally in an individual, was in fact dependent on the support of the whole of the upper classes of priests and merchants, tempered only by the fear of popular revolt.

We shall follow in this book the rise and fall—the developments

and differentiation—of the *class society* during its 5,000 years of existence. We shall see it in turn as a social form assisting, holding back, or destroying the chances of human advancement. At its very inception, however, there can be no doubt of its generally progressive character. It gave an enormous impetus to the development of techniques and to the beginning of a rational approach to them from which science was to arise.

3.3—*THE TECHNIQUES OF CIVILIZATION*

The discovery of metals

The organization of river-plain agriculture was the decisive economic factor in the first rise of cities. The major technical advance that accompanied it was the discovery and use of *metals*, particularly that of *copper* and its alloy *bronze*, which has given its name to the whole era of early civilization. However enormous was the subsequent importance of metals to technique and science, they cannot have acquired this importance from the outset. The word for " metal " comes from a Greek root meaning " to search," which implies their early scarcity. At first metals were such rarities that they were used only for luxury articles. The agriculture and most of the crafts of the city were carried on by stone techniques. Metal was not even strictly necessary to civilization. None of the great cities of the Mayas or the Aztecs ever knew it except for ornaments; all tools were of stone.

Metals, apart from gold and a little copper, are not found in the raw state, their extraction and preparation imply a long experience and even possibly deliberate experimentation. The original impulse may have come from the interest that primitive man, even in the Old Stone Age, had in all oddly shaped and oddly coloured objects. Bits of metallic ore were bound to attract attention, and in fact have been found in necklaces and other ornaments. It is perhaps more than a coincidence that there was a very considerable trade and use of malachite, the most easily reduced ore of copper, as eye-paint in pre-dynastic Egypt. The use of metals for tools must have been a secondary consideration.

The first of the metals, because it was the most obvious in the native state, was gold.[2.18] But gold nuggets, unlike the hard and brittle stones used for implements, were plastic. They

could be beaten out, and a technique of metal-working was developed long before metal could be extracted from the ore. Native copper nuggets, though not so conspicuous or ornamental, could be beaten out into pieces hard enough for tools. This was found to be easier if the metal was first heated or annealed before hammering. This association of metals with fire techniques probably led to the next steps, the reduction or smelting of carbonate copper ores and the melting and casting of the metal produced. Recent research [2.18] seems to show that these steps took place in this order. Both require higher temperatures than can be reached in an ordinary fire, and the evidence points to their association with the production of glazed pots in a kiln with a good draught. A major problem in accounting for the origin of metallurgy is that the localities of native copper or surface oxidized copper ores are usually in hills remote from agricultural centres. It is still an open question whether metallurgy started in the mining areas and the products were rapidly taken up in the cities, or whether both ores and metal were first accumulated in the cities and the technical advances made there. Even if the latter was the case, transport difficulties early in the metal age sent smelters out near the mines.

Effects of the use of metals

The production of metal implements and utensils is another technical advance marking a new qualitative change in man's control of his environment. Metal tools are far more valuable and durable than stone tools, and metal weapons are very much more effective than stone ones, both against animals and human enemies. Metal vessels can stand fire without cracking.

On the other hand, metals were for centuries very expensive. Copper ores are sparsely distributed in distant and inaccessible places and tin ores even more so. Both are needed for *bronze*, with its low melting point, which made *casting* feasible. Bronze is far harder than copper, and its use made metal superior to stone for all tools and weapons. Metals and their ores imply distant trade, and with it the inevitably high cost of primitive transport; this must have added very much to their price in the city. Consequently their use was restricted at first to adornment for the temples, utensils for the king's table, tools for the city craftsmen, and then, as war became more common, for weapons.

The craft of the smith

The techniques of metal-making and the use of metal tools were of enormous importance to other techniques and in enlarging the craftsman's knowledge of the physical and chemical properties of matter. Sheet and wire were made by hammering and drawing, and casting, welding, soldering, and riveting were developed extraordinarily quickly. These techniques were used to create rich and complex ornaments, vessels, and statues. Because metal-working in bronze, silver, and gold was developed at a relatively late period, unlike pottery and weaving, it was specialized from the start and seems to have been in the hands of close guilds of *smiths*. This was an occupational clan, one early example of what was to become the whole system of minor *castes* in India. The metal-workers must have had a very close guild, as many of their processes remained secret till recent times, or have been lost because no written record was left (p. 429).

The early smiths, apart from those involved in mining and smelting, were mainly concerned with working up metal from ingots or scrap. Most of them must have lived in the cities, but we know from the hoards of scrap and half-made tools they left behind that they must also have travelled around the country like a superior kind of tinker.[2.18]

The value of metal tools and weapons did not lie only in their durability. The fact that a metal tool could take a much thinner section than stone made it cut clean, not merely notch or break. Thus the use of metal tools, particularly the *knife*, *chisel*, and *saw*, transformed the working of wood and made jointed *carpentry* and coursed *masonry* practical on a large scale. The first machines, particularly the wheeled cart and the water-wheel, were only possible thanks to metal. Even in the basic craft of agriculture the ox-drawn hoe or plough became fully effective only when metal replaced stone for its earth-breaking *share*.

Transport

The mechanical inventions of the first civilization were destined to have immediate as well as long-term effects. The very existence of the early cities depended on the ability to organize the effective transport of materials in bulk. Food from the countryside was needed for thousands of people in the city; trade goods had to be exchanged with other cities, and

metals, wood, and even stone had to be fetched from distant forests and mountains. This led to great improvements and radical innovations in the means of transport which were to have far-reaching consequences to civilization, and especially to the growth of science.

The ship

As the early civilizations grew, first round large river valleys and their associated deltas and lakes, they must from the beginning have depended mainly on water transport. Under the stimulus of that need, the primitive dug-out canoes, the bundles of reeds, or the bamboo rafts were built up by almost imperceptible additions, continually tested by practice, into serviceable *ships*, capable of conveying goods in bulk. Indeed, the early political unification of Egypt was made possible and even necessary by the use of the Nile as a waterway. Early boats and ships were propelled by paddles or oars and were to continue to be so for many centuries. However, at some date around the beginning of civilization came another crucial invention—that of the *sail*. This enormously increased the range of shipping; but it is of prime importance as the first application of inanimate *power* to human needs, the prototype of the wind- and water-mills, of the steam engines and aeroplanes that were to come later.

The rivers and lakes were the training grounds for venturing on the sea, though here the fishermen may have anticipated the traders. Sea travel in turn imposed new problems in shipbuilding, demanding much firmer construction than was needed for river craft. Further—and this was a point of the utmost importance to later science—it imposed a need for finding the way when out of sight of land. The most primitive method was that of the land-finding bird, as in the legend of Noah's ark. Land-finding by the stars implies some idea of a map. *Navigation* by sun and stars was second only to the calendar in its demands for practical astronomy.

The wheel

As significant for the future advance of technique and science was the development of land transport which combined two critically important ideas: the use of *animal power* and the *wheel*. Animals had been tamed and bred, at first for food, to satisfy more amply the old hunter's needs. Now they had a new

function in doing work, in drawing wheeled *carts* and in taking the place of women in pulling a hoe, thus transforming it into a *plough*.*

The first use of animals for transport was probably with the pack-saddle. Early man, to judge from the absence of any pictures of him doing so, must have been very chary of riding even donkeys. After the pack-saddle may have come the *travois*—a pack tied to two poles trailing on the ground—still used by some Siberian tribes. This invention does not, however, seem to be the origin of the cart, for in the earliest of these we find the yoke and pole of the plough rather than the shafts of the *travois*. The need to move heavier objects that could not be broken up into loads, like tree-trunks for beams, or stones for great buildings, came only with the rise of cities. For this the first solution was the *sled*, probably only an enlarged version of the light sleigh of the forest hunters. Heavy sleds could be eased downhill, but along the level tree trunks came in handy as rollers.

The crucial transition between roller sled and *cart* was probably a city-inspired one, though, once made, the cart spread rapidly to country districts. The real ingenuity lay in securing a solid roller to the body of the cart so that it could turn without coming off. In early Mesopotamian carts and some Indian carts to this day the axle turns with the wheels and is held in place by leather straps. This was the first true *bearing*, though the *door*, with its post and socket, must have run it close. The next stage came in enlarging the ends, first with solid baulks to make *wheels*, and devising a leather and then metal tyre to hold them together. The first development of the wheeled cart seems to have been by the Sumerians, possibly before they came to Mesopotamia. The Egyptians, whose cities were never more than a few miles from the Nile, used boats for most transport; wheeled vehicles were introduced very late. The light, spoked wheel for war chariots, turning freely, came much later, near the end of the Bronze Age, for it required the extremely accurate joining of the *wheelwright*.

These inventions were to have enormous material and scientific consequences. The cart and the plough between them enabled agriculture to be spread over all open plains and so far beyond the limits of the old civilizations. The two-wheeled ox cart of the Early Bronze Age was the early prototype of the covered wagon that was, 4,000 years later, to open the

prairies of the New World. In level country, wherever plough and cart could be used, they added to the effective surplus of agricultural produce, as well as making possible foreign imports in bulk. The lever and inclined plane, already used in the great constructions of temples and pyramids, had laid the foundations of *mechanics*. The use of the wheel, from which were to come water-wheels and pulleys, was to build on these foundations a new edifice of theory that could reach from earth to the wheeling skies. The twelve spokes of the sacred wheel marked off the months of the year, while the wheel itself in motion became the sun-cross or swastika, a symbol first of innocent then of sinister portent. At the same time the increased possibilities and speed of transport by cart and even more by ship, together with the need to know the sources of valuable materials, led to deliberate exploration and to the beginnings of *geography*.

The invention and the subsequent development of all these new techniques furnished an enormously extended field for scientific understanding, just at the time when the organizational needs of the new civilization were bringing into being the intellectual means by which that understanding could be expressed and transmitted.

3.4—*THE ORIGIN OF QUANTITATIVE SCIENCE*

Reckoning, writing, and science

The wide scope of operations and the large quantities of materials and services involved in operations of the city temple provoked this qualitative change which marks the beginning of conscious science. In the first place, when they could no longer trust to their memories, the priests were obliged in some way to record the *quantities* of goods received and handed out. This implied the use of *measure*, first as a mere convenience—baskets of grain, jars of beer, pieces of cloth—but then, in order to make them comparable, some standardization was necessary. A set of definite temple or royal measures was adopted and gradually, for the benefit of foreign trade, partly co-ordinated between different cities. Probably later, but still very early, is the measure of *weight* implying the use of *balance* with its incalculable consequences for science. The balance must be a city product; in village economy there is nothing that cannot be counted or measured—a shoulder of mutton, a load of wood.

It is in the first place required for valuable metal which cannot be measured and where a " piece " is too indefinite, so that weights are needed. The balance, the only way of comparing weight, bears all the marks of being a *scientific* invention. Its prototype was probably the pole and basket load carrier *balanced* on the shoulder. It needed, however, considerable reduction in scale to be really useful for weighing precious metals (Fig. 3).

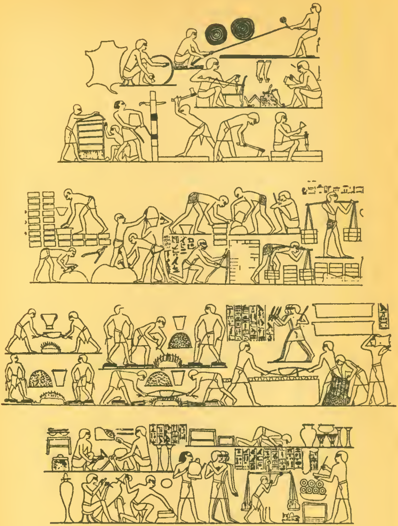
Numbers and hieroglyphics

Even before the standardization of measure it was important to record the *numbers* of objects, whether they were heads of cattle or baskets of grain, that were being collected or handed over. At first this would be done by making mere cuts on a stick, then by single strokes written on a tablet or lump of clay, then by more elaborate designations of large numbers. For the records, where what was in question might have been forgotten, the number symbol was followed by a picture or shorthand symbol of the particular object to indicate what it was that was being counted.

By extension these symbols came to cover actions as well as objects and so to stand for words, either by their meaning alone, as in Chinese, or in part sound–part meaning combinations, as in Mesopotamian cuneiform or the Egyptian hieroglyphics that seem to have been inspired by it.[2.20] The final simplification of the true alphabet, where the symbols stood for sounds alone and not for words, did not occur till the Iron Age. In this way *writing*, that greatest of human manual-intellectual inventions, gradually emerged from accountancy. As Speiser put it, " Writing was not a deliberate invention but the incidental by-product of a strong sense of private property." [2.44] First, official statements in the nature of propaganda, praises of kings, hymns to the gods, and last of all science and literature, came to be written down.

Mathematics, arithmetic, and geometry

But *mathematics*, or at least *arithmetic*, came even before writing. The manipulation of the signs for objects (as simple symbols) meant that it was possible for the first time to perform the elementary operations of addition and subtraction without counting the real objects in the field. For this it was a matter of matching one collection of objects against another. First came the standard collection, the ten fingers of the two hands, the



a

b

c

d

Fig. 3.—EGYPTIAN TECHNIQUES SHOWN ON TOMB OF REKHMIRÉ (c. 1470 B.C.)

(a) Rope-making (note swinging weight) and cabinet-making (note use of bow-drill, chisel, and saw).
(b) Brick-making and building (note balanced loads).
(c) Bronze-casting (note foot-operated bellows and absence of tongs).
(d) Finishing vases and weighing precious metals (note similarity of balance to brick carrier).

digits of arithmetic, the origin of the *decimal* system. In a pyramid text the soul of an Egyptian pharaoh is challenged by an evil spirit to show that he can count his fingers and triumphantly passes the examination. For more complicated counting, and for adding and subtracting, stones (*calculi*) could be used, which gave us the term for all our *calculations*. Later they were replaced by beads arranged in tens on wires, making the first and still very useful calculating machine, the *abacus*. The introduction of measure made it possible to extend adding and subtraction to quantities. The more complicated operations of multiplication and division came when shareable quantities were involved, particularly quantities connected with public works—the digging of canals, the building of pyramids.

The operation of building itself also contributed, probably even before land survey, to the foundation of *geometry*. Originally, town buildings were simply village huts made of wood or reeds. In cities, with a restricted space and danger of fire, houses of pisé or rammed mud were a great improvement. The next step was to have even greater consequences: the invention of the standard moulded block of dried mud—the brick. The brick may not be an original invention, but a copy, in the only material available in the valley country, of the stone slabs that came naturally to hand for dry walling in the hills. Bricks are difficult to fit together unless they are rectangular, and their use led necessarily to the idea of the *right angle* and the use of the *straight line*—originally the stretched line of the cord-maker or weaver (Fig. 3).

The practice of building in brick, particularly of large religious buildings of pyramid form, gave rise not only to *geometry*, but also to the conceptions of *areas* and *volumes* of figures and solids reckonable in terms of the lengths of their sides. At first only the volume of rectangular blocks could be estimated, but the structural need for tapering or battering a wall led to more complicated shapes like that of the pyramid. The calculation of the volume of a pyramid was the highest flight of Egyptian mathematics and foreshadowed the methods of the integral calculus.[2.35]

Also from building came the practice of the *plan to scale*. Such a plan for a town together with the architect's rule is for instance shown in the statue of Gudea of Lagash in *c.* 2250 B.C.[2.28.265] With these mathematical methods an administrator

was able to plan the whole operation of brick or stone building in advance. He could estimate accurately the number of labourers wanted, the amount of materials and food they would need, and the time the job would take. These techniques were readily extendable from the city to the country in the lay-out of fields, the calculation of their areas, and the estimate of their yields for revenue purposes. This is the origin of *mapping* and *surveying*. It was this practical use that later gave rise to the term for *geometry*—land measurement. *Mathematics*, indeed, arose in the first place as an auxiliary method of production made necessary and possible by city life (Fig. 4, p. 155).

Astronomy and the calendar

The ability to count and calculate, derived from practical needs of the temple administration, was of immediate use to them in another of their capacities: the making of calendars and the development of *astronomy* which this entailed. Early man must have paid some attention to the sun, moon, and stars, but was apt to be more concerned with the violent performances of the heavens, such as thunderstorms, than with the completely reliable and regular phenomena of day and night. Such a calendar as he needed was provided by the moon, around which had collected much ritual and myth,[2.46] but which at first made little call on mathematics or astronomy.

With the advent of agricultural civilization, the year rather than the month became important. When agricultural operations had to be planned on a large scale it was necessary to know when to start getting ready to do them. Of course Nature often gave fairly good intimations. The first of these, which were afterwards debased into the superstition of *augury*, came from the very practical linking of the birds with the seasons. The cuckoo is significant because he heralds the spring. He may even be thought divine for bringing it. An acute observer of Nature has a fairly good calendar without bothering to count the days at all.

However, in at least one place—the Nile valley—the flood is a regular annual phenomenon for which it is essential to prepare beforehand. The actual length of the year, 365·2422 . . . days, is not easy to find. It requires prolonged and careful observations of the sun and the stars. Such observations were carried out by the priests in Egypt, and already in *c.* 2700 B.C.

led to the compilation of a solar calendar that continued in use for thousands of years.

The Sumerians and their successors in Mesopotamia were too attached to the moon to accept such a simple solution. Instead they tackled the far more difficult task of reconciling the lunar and solar calendars. This required recorded observations extending over many generations and the development of accurate computations. It was here that there developed the sexagesimal system—360 degrees in a circle (near enough to the days in a year); 60 minutes in an hour; 60 "second" minutes in a minute—which we still use for angle and time measurements. These calendrical computations were carried out by means of extensive *mathematical tables*. These tables are elaborations of those used for business accounts. From them has come much of our *algebra* and *arithmetic*, including the all-important place notation that was to return centuries later as the Arabic (Babylonian, Persian, Hindu) numerals we still use.[2.35]

Astrology

The practice of observation carried out in the temples of all the ancient civilizations, including those of America, extended far beyond the needs of the calendar. The sun, as the regulator of the year, the bringer of the harvest, came to be worshipped as a god. The moon, though ousted from the primacy that it had in the time of the hunters, was not neglected, and observations were extended to the brilliant erratic stars, the planets, that acquired minor divinities of their own.

All this was far more than agriculture or even navigation required, but by then the calendar and the astronomy needed to draw it up had acquired religious significance. The calendar itself was necessary to fix an ever more complicated set of religious holy days, the scrupulous observance of which, as with our own *Sun*day, was considered essential to the preservation of the order of Nature.

Astronomy was finding other uses. Its study was, from the start, linked with religion. It dealt with the sky-world in which the spirits, particularly those of the sacred kings, lived after death. At first the sky-world was pictured very much like the world below. The Egyptians thought of it as a flat cover, resting on the hills, through which flowed the celestial Nile—the Milky Way. The Babylonians at first pictured it as the inside of a vast four-square tent from which the stars hung like

lamps.* It was only after the invention of the wheel that the turning of the sky on its axis round the pole could be accurately imitated. Chinese astronomy seems to have started from this idea of rotation. This is shown by the antiquity of the *pi*, a wheel-like object representing heaven which can actually be used to fix the position of the stars of the Plough. Chinese astronomy retained the dominance of the circumpolar stars rather than the ecliptic for many centuries.[3,4]

The idea of regular rotation of the heavens led to a great emphasis on the movements of the heavenly bodies. It was argued that if these regular recurrences in the heavens affected Nature and brought about the seasons, they must equally affect the condition of man. At first it was only the divine king who was *en rapport* with the skies; but ultimately the privilege became more common and every individual who could pay, might regulate his behaviour by the stars. The seven planets were completely domesticated and still preside over the days of the week. Even their order—Sun, Moon, Mars, Mercury, Jupiter, Venus—was originally astrological. Astrology was always intimately connected with astronomy and, in spite of its essential fallaciousness, it was the major reason why men occupied themselves for millennia with observations of the stars, which, had they not believed in astrology, would have seemed very remote and ineffectual.

Medicine

The other occupation that shared with astronomy the distinction of being an upper-class profession was that of medicine. But here, although the prestige was probably as great, the real success, because of the essential complexity of living systems, was bound to be much less. There was in fact practically nothing that a doctor of thoes times could do except deal with some obvious wounds, dislocations, and fractures, and try to prevent the patient from killing himself, or his relations from killing him by unsuitable treatment or diet. Where the doctors could succeed, however, was in diagnosis. They had in the city enough cases to enable them to compare one with another, and such comparisons, extended by conversation and codified by tradition, are themselves a beginning of science. Doctors, long before writing, carried on their traditions orally, first in closed clans which could then be widened by teaching and adoption (p. 131). From the noticing of

diseases, and even the recording of them—for we have some extraordinarily interesting examples in early Egyptian papyri [2.9] —arose the sciences of *anatomy* and *physiology*.

Prognosis—knowing how the disease is likely to end—was specially important in early times because the laws, at least of the Babylonians, show that an unsuccessful doctor was likely not only to be prosecuted but also even to have his eye put out if by any mistake he destroyed the eye of his patient. It is therefore not surprising that many of the descriptions of cases in an Egyptian papyrus end with the words " case not to be treated."

Official medicine codified the plants and mineral substances, knowledge of which had been handed down traditionally from the medicine men and wise women of primitive cultures. Some of these had been chosen for their manifest action as purgatives or emetics; others because in a more obscure way they had been found beneficial in some diseases, as the South American Indians had found quinine for malaria; but the majority were probably pure magic, based on resemblances such as that of the mandrake to the human body. The city doctors, however, could call on a far larger area for their drugs and could organize their production. It was from this source, rather than agriculture, that arose the science of *botany* and the first botanic or herbal gardens.[1.39]

Early chemistry

Chemistry never rose to the rank of a recognized science in the Bronze Age, or even till near the end of the Iron Age. Nevertheless its basis was being well laid in the multiple observations and practices of the metal-workers, jewellers, and potters. The process of smelting ores, of purifying metals, of colouring them, of adding enamels—all involve complex chemical reactions that had to be learned by many trials, mostly unsuccessful. The good results were embodied in recipes which had to be carefully handed down and scrupulously followed. We do not by any means know yet the full range of the achievements of these early chemists, but what is known is impressive enough.[2.37]

They were acquainted with at least nine of the chemical elements—gold, silver, copper, tin, lead, mercury, and iron,[2.18] as well as sulphur and carbon—and were using and distinguishing the compounds of others like zinc, antimony, and arsenic. They also knew a variety of reagents, dry and liquid, including

alkalis like potash and ammonia (as fermented urine) and alcohol as beer or wine. Their apparatus was limited to pottery and metal vessels; they had no stills and could not cope with spirits or gases.

One powerful impulse was to turn their method of work in the direction of a rational and *quantitative* science; namely the scarcity and value of the materials they dealt with. From the beginning precious metals had to be weighed and accounted for and the proportions used in alloying recorded and adhered to. *Chemical analysis* or assaying, involving the separation of metals already alloyed or mixed in ores, arose naturally out of the necessity of recovering the most precious metals and guarding against adulteration. It was a crucial step in the history of chemistry, and although we cannot precisely date it, we can tell when it arose by the appearance of objects of refined gold instead of the natural gold–silver alloy, electrum. We know from later sources some of the processes used, such as that of antimony for separating silver from gold, and cupellation for separating lead from silver. The astonishing success and persistence of these methods are brought out by the fact that the recipe for a cupel in an ancient Egyptian papyrus—namely bone ash moistened with beer—is still the recommended way of making cupels. The astonishing sight of the shining bead of live silver suddenly appearing from the mass of dull, mortified lead oxide made a deep impression. It became the centre of alchemical interest, and inspired spiritual analogies of purification by fire and the resurrection of the body glorious. Indeed, this may have been the origin of cremation (p. 125) (Fig. 8, p. 263).

Because we have no works on ancient chemical theory it does not follow that it did not exist. Though it may never have been formally expressed, the ancient chemists show in their products that they were acquainted with the general principles of oxidation and reduction and could introduce or remove non-metals, such as sulphur and chlorine.

As they were mainly concerned with making ornaments they understood particularly well how to produce colours, and since it was the appearance that mattered, they gauged the result by what it looked like. In trying to make copper look like gold, they produced *brass*; in trying to make the blue turquoise or lapis, they produced a blue *glaze* that was the origin of *glass*. The fact that they were masters of many startling transformations led them to consider that nothing was impossible to their

art. This healthy scientific optimism was to degenerate later into the mystical superstition of *alchemy*.

The early chemists never thought of themselves as such, but as metal-workers, goldsmiths, and jewellers. They were highly valuable technicians, closely associated with the priesthood and the court, but they were hand-workers at a particularly dirty trade. Their knowledge could not be presumed to be a science on a par with astronomy, mathematics, and medicine. It was an art, but the black art with great magical possibilities (pp. 160, 202).

3.5—*THE CLASS ORIGINS OF EARLY SCIENCE*

It will be seen even from this abbreviated sketch of the scientific achievements of the early civilizations what enormous advances necessarily followed from the foundation of cities. It should also be clear that the scientific, as distinct from the technical advances, were limited to those arising out of the problems of large-scale administration. They were therefore developed by the priests, and also restricted to them, because only the priests had access to the means of recording and calculating. The very term hieroglyphics—priests' writing—brings home that limitation. The association of learning and science with one class in the newly formed class society was to remain its outstanding feature, with a few significant exceptions (pp. 884 f.), down to our own time. The prestige of mathematics, astronomy, and medicine as noble sciences of the ancient civilizations so impressed the Greeks, and after them the people of our own Middle Ages, that, with the minor addition of music, they remained the pillars of higher education, while baser sciences such as chemistry and biology have still to struggle for cultural recognition. Further, the main programme of science until the eighteenth century, the understanding of the motions of the heavens and their connection with the vicissitudes of life on earth, was already established in outline almost from the beginning of ancient civilization.

One significant feature of techniques and culture in the early city States was the extreme rapidity of their development even judged by modern standards. For example, it is known that the construction of the pyramids of Giza, with their enormous size, geometrical and astronomical accuracy, and flawless masonry, evolved from that of simple rock-cut tombs in a matter of two or three centuries from *c.* 3000 to *c.* 2700 B.C. Such a

speed implies, as does the character of the work itself, the existence of able and practical men, willing to invent and try out new methods over an enormous field of activities. At first it would appear that the innovators were themselves technicians; the legends of such culture heroes as Imhotep, Tubal-Cain and Dædalus show them as craftsmen who both invented and made wonderful new things themselves.

Scribes and workers

But soon after the foundation of the first cities, about the era of the first dynasties of Egypt or the early kingdoms of Mesopotamia, it is apparent that the needs of large-scale organization were already leading to the divorce of the organizers from the actual technical processes themselves. As they became more numerous and indispensable, they became a caste, markedly separate from the craftsmen and with a great feeling of superiority to them. A very interesting example of this new attitude is shown in a fragment from an Egyptian papyrus of uncertain but early date. It purports to be the instruction of a father to his son whom he is sending up to a " College for teaching scribes ":

> I have considered violent manual labour—give thy heart to letters. I have also contemplated the man who is freed from his manual labour, assuredly there is nothing more valuable than letters. As a man dives into water, even so do thou sink thyself to the bottom of the Literature of Egypt. . . . I have seen the blacksmith, directing his foundrymen, but I have seen the metal-worker at his toil before a blazing furnace. His fingers are like the hide of the crocodile, he stinks more than the eggs of fish. And every carpenter who works or chisels, has he any more rest than the ploughman? His fields are wood, his tools of tillage are copper. Released from his work at night, he works more than his arms (during the day). At night he lights a lamp. . . .
>
> The weaver sitting in a closed-up hut has a lot that is worse than that of a woman. His thighs are drawn up close to his breast, and he cannot breathe freely. If for a single day he fails to produce his full amount of woven stuff, he is beaten like the lily in the pool. Only by bribing the watchmen at the doors with (his) bread-cakes can he obtain for himself the sight of sunlight. . . . I tell thee that the trade of the fisherman is the worst of all

> trades; truly he does not exist by (his) work on the river. He is mixed up with the crocodiles, and if the papyrus clusters are lacking he must cry out (for help). If he is not told where the crocodile lurks, fear blinds his eyes. Verily there is no occupation than which better cannot be found except the calling of the scribe which is the best of all.
>
> The man who knows the art of scribe is the superior through that fact alone, and this cannot be said of any other of the occupations I have set before thee. Verily each worker curses his fellow. No man says to the scribe, " Plough the fields for this person ". . . . One day (spent) in the chamber of instruction is better for thee than eternity outside it; the works thereof (endure like) the mountains. . . . Verily the goddess Rennit is on the way of God. She is by the shoulder of the scribe both on the day of his birth and when, having become a man, he enters the Council Chamber. Verily, there exists no scribe who does not eat the food of the King's House (life, strength and health to him!).[2.10]

It will be seen that already white-collar, or at least white-skirt, occupations are considered to be morally and practically superior, and even worth the intense labour of coping with the fantastically complicated writing and calculating systems of early civilization. The priest-administrators, separated from dealing with material things, tended to elaborate their own symbolic methods and to impute an independent reality to them. In one sense this was valuable, since it gave at least a few select minds the leisure to think, and indeed they were able to create from those symbols the abstract constructions of mathematics. The great achievements of Egyptian and Babylonian reckoners were the foundations on which the later and more abstract mathematics of the Greeks were built. Nevertheless, this preoccupation with symbols permitted the retention of much more primitive ideas, such as the sympathetic magic of the hunting days, and a further enhancement in the power of spirits.

Magic and science

Indeed, with the waning of the first impulse of technical advance, magic seemed to become even more important than ever. From being a progressive, if erroneous, explanation of how things work in the world, it became a hindrance to the advance of effective thought. Coming from priests,

increasingly divorced from the processes of production, it purported to find solutions to real problems which were seemingly far too easy. By relegating the control of health or success to spirits it prevented the search for useful actions to secure them. It also favoured the use of loose analogies as supposed explanations of natural events in terms of the actions of divine spirits. The world of Nature was seen as merely an enlarged version of the world of man. In fact, every advance of human technique was an invitation to try to understand the rest of the universe in terms of such successful human activity. The major creation myths offer just such explanations. The making of the world is likened to the work of a supreme irrigator separating land from water, and the making of man to the work of a supreme potter moulding him out of clay. Such myths are even more *technomorphic* than *anthropomorphic*.

With due allowance for the enormous difficulties of formulating general scientific theories before the working out of scientific language, we may recognize in many myths the prototypes of scientific theories. In them the forces of Nature are personified, but perhaps their priestly authors took the personification as a mere manner of speaking. Certainly the theories they contained were easily sensed by the Ionian Greeks, and retold without the gods (p.120).[2.47; 2.21]

Until science had advanced to the point at which the major part of the environment that mattered to mankind was controllable rationally by direct action—and that achievement is a very recent one—it was, however, very difficult to check the failure of the spirit theory to give man any practical control of Nature. The spirit way seemed no worse than any other, and, by a judicious combination of faith and probability, could even be imagined to work very well. People usually recovered from diseases, crops usually grew, and the sun could be counted on to rise every morning.

However, so long as men held to spirit explanations of natural phenomena, the growth of science was actively inhibited. For not only was any attempt to achieve rational understanding and control deemed from the outset to be useless, but also it might even be harmful, as the spirits would undoubtedly feel annoyed at such attempts to cheat them of their prerogatives. This is only another way of saying that it endangered the livelihood of the priests, who had a vested interest in a spiritual magical theory of the universe, especially when the early temple

establishments decayed, and the priests became increasingly dependent on the offerings of the faithful.

The danger to the aristocracy of the gods of attempting to control the forces of Nature is the fundamental meaning of the myth of Prometheus.[2.45] Fire from the first belonged to the heavens; man had no right to take it for himself. What the priests wanted was piety—unremitting practise of the rituals of propitiation, the careful observance of all taboos, and resignation to the will of the gods. As long as these views were supported by authority—and they have not yet disappeared from society—it was even impious to inquire too closely into the method of working of the universe. Such inquiries were bound to be resented by the heavenly powers, and their resentment would be vented not only on the inquirer but on the whole of society. The forces of religion were, from the beginning, closely identified with the maintenance of class rule. When, some centuries after the first founding of cities, the ruling classes ceased to favour material and technical progress, religion was bound to restrict intellectual advance.

3.6—*SUCCESSES AND FAILURES OF THE FIRST CIVILIZATIONS*

Taken as a whole, however, the early civilizations did succeed in making and sustaining an enormous advance in techniques and ideas. The high level of their technical achievements is shown by the fact, so common that we hardly pay attention to it, that for the greater part of our lives we are surrounded with and use equipment evolved at that time and scarcely altered in the intervening 5,000 years. Our chairs and tables have not changed since the first Egyptian carpenters solved the difficult problems of wood joinery. Armchairs with wicker seats and claw feet are known from *c.* 2500 B.C. We still live in rooms with walls and ceilings of stone, brick, and plaster; we eat from the same kind of dishes; we wear clothes made of the same kinds of cloth.

Even our social institutions have not changed to an extraordinary extent—far less than the change between the institutions of primitive communities and of the first cities. We have merchants, magistrates, and soldiers just as they had; and the political troubles of our time were not unknown to them. In other words, most of us are still living in the class society that originated with the first cities.

Technical stagnation

The great burst of technical innovation that came with the beginning of city life in the great river valleys of Mesopotamia, Egypt, India, and China did not last more than a few centuries, roughly from 3200 to 2700 B.C. It was followed by a relatively far longer period of cultural and political stagnation. Particular cities rose and fell; one dynasty of priest kings superseded another. There were irruptions of barbarians and even barbarian dynasties, but there was no essential change in the pattern of production. It remained based on irrigation agriculture, supplemented by trade with outer regions. All the wealth that was accumulated and consumed in the cities came from the surplus of city-directed agriculture. Because the surplus was relatively small, only comparatively few of the people could be supported on it, and these tended to form an exclusive class. The successors of the original administrators who worked to improve agricultural techniques became increasingly divorced from the process of production. Their only interest was to secure as much of the product as possible for themselves. From generators of wealth, they became exploiters. They demanded ever more and more for their private enjoyment and for the building and service of increasingly magnificent temples and tombs. This meant the impoverishment and virtual enslavement of peasants and urban craftsmen, and led to conflicts which weakened the city States and ultimately put a stop to their intellectual and technical progress.

Of one of these events we possess fairly full details. In the Sumerian city of Lagash, in its time—2400 B.C.—the chief city of southern Mesopotamia, there occurred what may justly be called a social revolution. A certain Urukagina seems to have seized power from the rulers of another dynasty and set under way a whole series of social reforms designed to limit the oppression of the bureaucracy, the priesthood, and the rich. Records of these have come down to us in which the contrasts between the old and the new deal are emphasized. Graft and corruption were put down and those convicted of them were dismissed, together with a general cutting down of an army of revenue officials and inspectors. The priests were deprived of many of their privileges and the fees they charged for burials, weddings, divorces, and divination cut to a third or less.

The reforms, however, did not last. The new deal did not destroy but only curbed the ruling class, and its members took

the first opportunity to ally themselves to the ruler of the rival city of Umma and launch a war in which Lagash was pillaged and destroyed. One of the loyal priests sadly records on a tablet: "Of sin on the part of Urukagina king of Girsu, there is none. For Lugal Zaggisi patesi of Umma may his goddess Nidaba bear their sin upon her head." 2.28.176 The success of the conqueror was shortlived. He was defeated in his turn by Sargon, the first king of Akkad, the founder of the first world empire, who was, or claimed to be, like Moses, a foundling picked up by a gardener.

War

The ending of this story brings out another potent source of unbalance of early city economy—the organized violence of war. The apparent limit to the exploitation of the local agricultural population could be overstepped by an extension of the area of the city. Up to a point this could proceed peacefully, but if several cities were following the same policy in a restricted area it led to conflicts and to the evolution of a new institution, that of war. War, in its full sense, is indeed a product of civilization. The fighting which recurred between tribes in the hunting or even in the pastoral stage was more in the nature of football matches than of sustained campaigns. Although cruel in detail, it could have very little general effect on a culture where, in any case, it was impossible to concentrate large bodies of warriors or maintain them in the field for more than a few days at a time. Once cities existed, however, that situation completely changed; armies could be heavily equipped and be fed from the surplus food stocks. The upper classes who controlled city governments had strong economic incentives for war. Their wealth depended directly on the area they could exploit, and cultivated land could be taken from another city together with the peasants who tilled it. Beyond that lay the possibility of seizing material, animal, and human booty.

War made the recruiting and leading of armies a vital necessity, and this changed the character of government and the State. The principal function of the head of the State changed from that of a director of agriculture and public works to that of a war leader—from priest to king. Another effect was once more to depress the position of women. In the first phase of civilization women had maintained the great importance they

had gained in the village cultures. As war became more important their administrative functions were taken over by men, though they never sank to the position of domestic slaves that was to come with the Iron Age.

Warfare and technique: the engineer

As warfare became more the rule than the exception, and the city began to be distinguished from the village by its defensive *wall* and its fortified *citadel*, the direction of technique began to be more and more influenced by the needs of the armies. Even the newly emerging science was bent in the same direction. Technical progress in weapon construction went on even at a time when other technical progress had almost stopped. We have only to think of the prestige attached in legend to such figures as Vulcan or Wayland the Smith to realize the importance of the armourer to the warrior. Even more important in the long run was the invention of military machines, such as catapults and moving towers, which demand an appreciation of the principles of mechanics. The need to make and service such machines, to build earthworks and drive mines, gave rise to the profession of the *engineer*, first and foremost a military profession, though originally drawing his skill from civil sources.

Other and more remote aspects of war also stimulated science. The problems of the supply of armies, including the making of roads and canals,[2.50] were among the most important; so was the design of fortifications, one of the earliest examples of plans to scale (Fig. 4a, p. 155). Plato considered that the only practical use for geometry was the drawing up of ranks and files in an army. Without war, or the social system that gave rise to it, the arts of peace could have advanced far more rapidly. But it may at least be said for the association of science and war that war kept science alive at a time when other aspects of culture were decaying.

Trade and empire

Partly by war, partly by a system of alliances based on trade, the originally independent city States tended to become merged into larger units either under the stable and overwhelming preponderance of one city, such as Memphis in Egypt, important not so much in itself but as the sacred city of the god-king, or under a shifting sequence of predominance among cities, such as the successive *empires* of Ur, Larsa, Isin, and

Babylon in Mesopotamia. In Egypt the concentration of power in the hands of the god-king Pharaoh and his priestly administration (*Per-aah* means big house = Whitehall) was such that enormous and economically unremunerative works like the pyramids could be undertaken. In Mesopotamia the cities were more equal and, though in the aggregate the wasteful expenditure of the upper class may have been as great as in Egypt, it was never so concentrated. In India before the Aryan invasion large city States with citadels, temples, and baths, similar to those in Mesopotamia, existed, but, lacking an understanding of their script, we know too little about them to assess their social structure.[2.37a] In early China the prestige of the emperor, the son of heaven, seems to have corresponded more with that of Pharaoh, though for a very large part of its history China has been divided into a number of warring States.

Empire and the supreme god

One result of the growth of empires was the precedence it gave to the god of the ruling town over those of the conquered or federated towns. Amon, originally the ram totem of the nome or parish of Thebes, became, with the rise of the Theban empire, joined to the hawk totem sun-god Ra, as Amon-Ra, lord of the gods. The local god, Marduk, became equally important in Babylon. The power of the god grew and waned with that of the empire, but it left behind the idea of one supreme god as ruler of all the world. Akhnaton tried to realize this idea officially in Egypt with his worship of the sun disc, but failed. It was left for the then obscure tribes of the Jews to succeed and to found modern monotheism.

3·7—*THE SPREAD OF CIVILIZATION*

While civilization stagnated at the centre its influence was spreading wider and wider. The existence of empires accentuated a problem that must have arisen with the very beginning of river-valley civilization—the relation of the city States to their less advanced neighbours in the open country and the hills. Civilization had provided better techniques, such as those of the plough, the wheel, and the metal sickle, applicable to farming in lands other than those where it originated. It therefore tended to spread in a variety of ways. One of these was simple trekking. The villagers, when the city territory

failed to absorb the growing population, moved off with their herds and carts into wilder, less hospitable but roomier country, and thus village communities spread all over the arable lands of Europe, Asia, and Africa and possibly also to America. In this spread many of the more complex products of civilization were necessarily lost or simplified, so that it becomes difficult to distinguish between civilized emigrants who had gone native and people of simpler cultures that had acquired, by transmission from neighbour to neighbour, some of the techniques of civilization.

Another way of spreading civilization was through the trader, and particularly the miner, those more adventurous spirits of the cities who went out into the wild borderland not to settle but to collect local produce of value, especially precious stones, ores, and gold. Because the traders had to give city products in exchange they served to spread the needs and, to a lesser extent, the productive methods of civilization. They also inevitably came into conflict with the local population, and invoked the help of their home governments to protect them. This led to a third way in which civilization was spread, the way of political and military interference that we still associate with *imperialism.* The records of the rulers of ancient Egypt and Mesopotamia are full of accounts of punitive or raiding expeditions to the gold mountains, the ivory country, or the pearl islands. Nor was interference limited to military action; as much could be achieved by discovering and making use of mutual antagonisms between foreign tribes or between rival factions inside them. The profession of *diplomacy* long antedates classical civilization.

The first barbarians

The expeditions led sometimes to actual extensions of settlements under the control of the parent city, as for example, the Babylonian mining settlements at Dûr-gurgurri, though this form of *colony* is much more characteristic of the later Iron Age. The main result was to generate increasingly effective opposition to the city empires. In time the institutions of the peoples in an area hundreds of miles round the centres of civilization had been changed by their intercourse with it. This was the area of the *barbarian* fringe. The barbarians were able to pick up items of the material culture of the cities, especially those which could be easily transported and would involve the least

change in their own habits. These were primarily weapons, which, though expensive, could bring in a far greater return than their cost if used in raids on the wealthier centres.

The tribal institutions of the barbarians were also transformed by introducing private property, emphasizing the role of the warrior, and increasing the authority of the chiefs. The effects were greatest in the cultures of pastoral peoples, who were highly mobile, unassimilable by civilization, yet dependent on it for many necessities such as tools and weapons, as well as for ornaments, which they had not the skill to make.[2.1a] The relations between the barbarians and the city States were variable and complex. Strong empires played one barbarian tribe against the other, raided and enslaved them. Weak empires were undermined by the importation of barbarian slaves and soldiers.[1.6] In the end they were often completely overthrown and ruled by barbarian dynasties which usually soon acquired the culture of the cities.

Slavery

One result of the relations between the city States and the barbarians was the steadily increasing importance of slavery. The institution of slavery, the ill effects of which dog the world to this day, goes back to the beginning of the river cultures. In the days of hunting or early agriculture there was little surplus. A working man did little more than earn his keep. Prisoners taken in inter-tribal feuds, if they escaped being sacrificed, were usually adopted; there was no point in enslaving them.

In civilized countries, on the other hand, an agricultural labourer could produce far more than it cost to keep him. That made the taking and using of slaves an attractive proposition. Slave-raiding from other cities, or more easily and profitably from barbarians, soon became an accepted practice.

The full development of slave-based agriculture was not to come till the Iron Age, but from the beginning of the Bronze Age it had started to exercise its ill effects on civilization. Bound prisoners, intended for slavery, are represented in the oldest Sumerian carvings of about 3000 B.C.[2.28] The existence of propertyless and also rightless slaves was bound to have a depressing effect on the status of free workers. By its association with that of slaves their work became base and menial. There was little incentive or opportunity for the free workers and none at all for the slaves to improve techniques, and the

upper class scorned them. As a result the scientific approach which had been so successful in the upper-class sciences of mathematics, astronomy, and medicine was cut off from the problems and the information that were to be found in the trades, and for long did not spread to the black art of chemistry or the lowly practices of agriculture.

The political ill effects of slavery were often more immediately disastrous. The more a city depended on slaves the less it was able to look to its own defence, and the more likely were the barbarians to become acquainted, as escaped slaves or later as mercenary soldiers, with the war technique of the cities themselves and to be able to use that knowledge to overthrow them.

Decadence

For several centuries before their fall, that is, roughly after 1600 B.C., the ancient civilizations of the West, though not those of China, seemed to have lost any capacity for progressive change and were becoming increasingly decadent. Although the framework of civilized life was maintained, art and literature became conventional and religion tended to become buried in an increasingly complex mass of ritual that could appropriately be called superstition. Though much had been lost or forgotten, some science, such as astronomical observation, was kept up and even developed; some degenerated into superstition, such as the careful examination of the livers of sacrificed animals used for foretelling the future. This is only one example of the use of systematic study of obscure phenomena for telling fortunes, cheiromancy (or palmistry), oneiromancy (or dream interpretation), many of which are still with us, either in their original form or in the games of chance and skill like dice, cards, and chess derived from them. In so far as they sharpened the acuteness of observation and the methods of codifying results they have some part in experimental science. One key discovery, that of the compass, was probably made by a Chinese geomancer (p. 235).

3.8—*THE LEGACY OF EARLY CIVILIZATION*

Nevertheless what remained to be handed on to its successors must have been an impressive and valuable stock of knowledge —far more than the spade of the archæologist is ever likely to

reveal to us. At the same time the archæologist is certain to know much that would not be known to people living a few hundred years after any event. Although the sources of knowledge may have been forgotten, many of its usable parts are likely to have been assimilated in an unacknowledged form. As the knowledge and practice were alive they could be learned by word of mouth and by the example of the practitioners. Only a certain amount of knowledge was assimilable by new cultures with different social and economic structures. The enormous accumulation of history, poetry, and literature of those times was largely lost with the knowledge of the hieroglyphic and cuneiform scripts in which they were written. The little that has survived in the Bible shows the level to which they reached. Much priestly science must have gone too. Techniques fared better; both the equipment of civilized life and the tools with which it was made largely survived and are in use today (p. 91).

The science and techniques of the Iron Age and even of the Greeks are largely derived from those of the ancient world, for the most part without acknowledgment. Indeed, in the case of techniques which are embodied in material and durable objects we can be sure that this has occurred. Many ideas or discoveries have been attributed to a Greek philosopher for no better reason than that he was the first known to us to have expressed them or been credited with them. Further research often reveals an earlier origin in Egypt or Mesopotamia, and we have no reason to believe that the present verdicts of archæology are final.

The heirs of the old civilization, the men of the Iron Age, had themselves no doubt about the greatness and magnificence of the empires that they had helped to destroy. Echoes of the life of those times are to be found in the *Iliad* and the *Odyssey*, themselves tales of city sacking and piracy. The poets contrasted their own hard lives and mean culture with the power, the luxury, the beauty, and most of all the peacefulness, of the old cities. They revered the wisdom of the Ancients and looked wistfully back at the age of gold.

Chapter 4

THE IRON AGE: CLASSICAL CULTURE

THE period covered by this chapter is one of crucial importance in the history of mankind and especially in the history of science. From the middle of the second millennium B.C. a number of causes—technical, economic, and political—brought about the transformation of the limited civilization of a few river-basins into one which embraced the major cultivable areas of Asia, northern Africa, and Europe. The civilization of the Iron Age, wherever it was developed, was less orderly and peaceful than that it replaced, but it was also more flexible and rational. The Iron Age did not provide such enormous technical advances as marked the outset of the Bronze Age, but such advances as it did achieve, based on a cheap and abundant metal, were more widespread not only geographically but also among the social classes.

In this chapter we shall deal primarily with the Iron Age in the Mediterranean area—the classical civilization of the Greeks and Romans. This is partly because it is so much better known than that of contemporary cultures of India or China. A more cogent reason, and one that relates particularly to the purpose of this book, is that it was that Mediterranean region which gave birth to the first abstract and rational science from which the universal science of our own time is directly derived. As we shall see in subsequent chapters, the civilizations of India and China had great contributions to make to the common culture, particularly in mathematics, physics, and chemistry, and their applications, like the compass, gunpowder, and printing. However, the contributions entered into the main tradition of science and technology only after its outlines had been fixed in its Hellenistic form.

4.1—*THE ORIGINS OF IRON-AGE CULTURES*

The barbarians who overran the Bronze Age cultures of the ancient east had been unable to form stable states in their own homelands, for the most part covered with forest or dry steppe,

as long as they lacked the means of establishing some settled form of agriculture. In the latter half of the second millennium B.C. these conditions were achieved, thanks to a combination of material and social factors that we are only now beginning to understand. Of these one was the penetration and transformation of barbarian clan societies through the influence of the class economies of the cities with their emphasis on private property, chieftainship, and weapon production.

The impact of the discovery of iron

These tendencies were powerfully, perhaps decisively, aided by the discovery and use of a new metal, *iron*. Where and how iron was first made in quantity is still a mystery. The first iron used was the native iron from meteorites treated by heating and hammering like copper, but this was too rare to be anything but a precious metal. The first iron to be smelted from its ores was probably a by-product in gold-making [2.18] and must have been even rarer. Iron in usable quantities seems to have first been smelted from the ore somewhere south of the Caucasus by the legendary tribe of the Chalybes, in the fifteenth century B.C., but it did not appear elsewhere in sufficient quantities for its use to be economically and technically decisive until about the twelfth century B.C. The wide distribution of iron and the ease of iron-working ended the monopoly of civilization of the old river empires of Egypt and Babylonia. Two other developments hastened the process—the appearance of mounted *horsemen* from the steppe lands where the wild horse, far more powerful than the ass, had been tamed, and rapid improvements in the performance and building of *ships*, itself a by-product of iron technology.

The metallurgy of iron

The iron used in antiquity, indeed up to the fourteenth century A.D. in Europe, was made by a process of low-temperature reduction by charcoal in a small, hand-blown clay furnace. The resulting *bloom* of spongy, unmelted pure iron was beaten out into bars of relatively soft *wrought iron* from which more complicated forms could be made by *forging* and *welding*. The first elaboration of the techniques of iron-making and -working must have been the fruit of long and difficult experience. This technique was totally different from that for copper and

this probably explains why iron metallurgy came so late Once established, however, it required nothing but the simplest equipment and could be quickly taught or picked up. Where-ever there is wood and ironstone—that is, almost everywhere—iron can be made: once you know how.

Iron had one serious disadvantage as a metal in early times: it could not be melted for lack of sufficient blast to the furnace, and casting was therefore reserved for bronze, except in China, where cast iron was made as early as the second century B.C.[2.18] Iron did not displace bronze; it merely supplemented it for common purposes. More bronze was made and worked in the Iron Age than ever in the Bronze Age itself. The iron made by the bloomery and forging process was a wrought iron or very mild steel; it was tough but relatively soft. Much harder true steels were known—chalybs from the Chalybes, ferrum acerrum, sharp iron, acier—but their method of manufacture was kept a deep secret among the tribes of smiths. The world of science was not to know it until the work of Réaumur in 1720 (p. 429). The secret was essentially one of getting more carbon to combine with the iron and then hardening by tempering and quenching. The best steels were those made by the Chinese—seric iron—and by the Indians, whose *wootz* steel [2.18] was exported to make the famous damascened blades. Good steel was so rare and highly prized that the swords made out of it were deemed to be magic, like Arthur's Excalibur or Siegfried's Balmung of later times. Tempered steel was far rarer than bronze and except for use in weapons was to play no important part in technique until the eighteenth century.

The introduction of iron coincided with a period of folk wandering. More or less barbarized tribes came down from eastern Europe or the Caspian into the eastern Mediterranean area from the seventeenth century B.C. onwards. Similar movements of Hittites, Scythians, Persians, and Aryan Indians were occurring in Asia. The great mobility of the horsemen and the sea peoples and their abundance of new weapons made it difficult for the old empires to put up an effective military resistance. We may suspect that military failure was an index of lack of support from the people of the older civilizations, who were more likely to sympathize with the invaders than with their own inefficient and rapacious rulers. Further, the iron age peoples, once they settled down, showed themselves capable of building prosperous agricultural or trading com-

munities on hitherto fruitless land. The result was to reduce the political and economic pre-eminence of the early river-valley civilizations to such an extent that they no longer figured as the main centres of human cultural developments, although many of their cultural, material, and spiritual achievements were transmitted and even some of their records were preserved.

Instead, the effective foci of advance moved to the periphery of the ancient civilizations, the settlements of the nearer barbarians, who had managed to overrun the older centres of civilization but who developed their culture largely outside them. The Aryan Indians, the Persians, the Greeks, and later the Macedonians and Romans fell heirs to the old civilizations of Egypt and Babylonia. The position of China was exceptional; surrounded largely by steppe, desert, and mountainous areas, there was little possibility of the building up of agricultural barbarian States beyond its boundaries. The barbarians that repeatedly moved in were all absorbed by ancient Chinese culture. That basically bronze age culture, though profoundly changed by iron age techniques, has retained its continuity right down to our own time.

Axe and plough

The destruction and wars of the early Iron Age were, however, not without their compensations. The substitution of new cultures for old meant certain losses of continuity, but it also meant the sweeping away of much accumulated cultural rubbish and the possibility of building much more effective structures on the old foundations. If the mounted warriors and the shiploads of pirates stand as symbols for the destructiveness of that period, the woodmen with their axes and the peasants with their iron-shod ploughs amply made up for the destruction. The earlier use of metal was essentially for the luxury products of city life and for arming a small *élite* of high-born warriors. Bronze was always too expensive for common folk, who still had to rely for the most part on stone implements the form of which had scarcely altered from neolithic times. Iron, however, though originally, and for many centuries, inferior to bronze, was widely distributed and could easily be produced and worked locally by village smiths.[2.18] The effect of the abundance of iron was to open whole new continents to agriculture; forests could be cut down, swamps could be

drained, and the resulting fields could be ploughed. Europe, from being literally a backwoods, became a new "golden west"—in the sense of its wheatlands rather than of its gold, which was largely exhausted at the end of the Bronze Age. The resultant increase in population rapidly altered the balance of power between the dry farming of the West countries and the old river-irrigated cultivations of the East.

Ships and trade

Another feature of the disturbed times of the Iron Age that was to be of incalculable importance to human thought, and particularly to science, was the use of the sea-ways in spreading culture much more rapidly than the old overland routes could possibly do. What was more important was that transport by sea was many times cheaper than by land. With the greater facilities for ship-building provided by iron tools there were better and larger ships and more of them. In the Mediterranean the initiative in shipbuilding had been taken by the Cretans in the Bronze Age. The breaking up of their sea empire, first by the land-based half-Greek Mycenaeans and later by the more barbarous Achæans from the Balkans and by kindred tribes in Asia Minor, was the signal for a great period of piracy and sacking of cities. The immortal story of Troy records one of these expeditions. Naturally piracy made trade difficult but it also made it profitable, and former pirates, attracted by this or deterred by more effective local defences, gradually turned to trade, exploration, and colonization.

In the Iron Age trade ceased to be a matter concerned only with a round dozen great cities, like Thebes or Babylon, and became more and more divided among the hundreds of new cities that the early iron age peoples, such as the Phœnicians and the Greeks, were founding all over the shores of the Mediterranean and the Black Seas. Only places near the sea could get the full advantage of iron age culture. In countries far removed from it the Iron Age certainly brought greater possibilities for agriculture and warfare, but, where there was no way of moving bulk products over long distances, such countries could not progress economically even as far as the bronze age civilizations with their river transport. They were consequently unlikely to produce anything radically new. The Assyrians, a typical land-based early iron age people, were distinguished mainly for their military ruthlessness. They pre-

served for some centuries the old Babylonian culture, including the continuation of astronomical observations invaluable for the science of the future, but added little to it themselves. This advantage of the sea-way could not be fully offset by roads such as those made first by the Persians and later by the Romans. These were of administrative and military rather than economic value. Land transport in bulk could not begin to be economical until the development of efficient horse harness in the Middle Ages (p. 232). Even then it was not practicable over large distances till the making of good roads in the eighteenth century. It was the ease of water transport that gave first the Mediterranean area and later all Europe, with its indented coastline, an advantage over Africa and Asia.

China, with its network of rivers, canals, and lakes, had some of the same advantages but, as it retained, even through periods of warring States, bureaucratic governments of a modified bronze age type, it missed many of the economic and political developments of the Iron Age.

4.2—*IRON AGE CITIES*

Politics

In its early stages the Iron Age meant a return to a smaller scale of economic unit. Early iron age cities rarely had populations of more than a few thousands, as against the hundreds of thousands of bronze age cities. By the fifth century B.C., with the spread of slavery, much larger cities were possible, Athens had a maximum population of 320,000, of whom only 172,000 were citizens, while Rome at the height of its power had about a million. The first cities were formed by the agglomeration of a dozen or so villages.[2.46] This, however, did not mean a return to neolithic conditions, but, for the population at large, to one with standards as high, or higher, than that of the Bronze Age. The iron age city had inherited all it could use of the arts of the bronze age cities, that is, all but the organization of large-scale works. Early iron age cities, with their restricted areas, rarely went farther than fortifications, harbours, and occasional aqueducts. Also it had, in addition, the use of a metal that enormously improved agriculture and manufacture and it did not need to be self-sufficing: it could rely on trade for necessities as well as luxuries. This was possible only because improvements in

the methods of production enabled goods to be made for a market. The Iron Age is the first in which *commodity production* becomes a normal and indeed an essential part of economic activity.* Another social economic feature of the Iron Age was the use of slaves not merely, as of old, for service but also as a means of producing for the market. This was mainly in agriculture and mines, but it spread also into manufacture. Slavery, as we shall see (p. 164), grew steadily in importance till it became the predominant form of labour. This was itself a substantial factor in causing the breakdown of the whole culture, with the consequent turning of slaves and poor freemen alike into a common people of serfs (p. 180).

The iron age city became, almost from its inception, a well-placed centre for manufacture and trade, able to get from abroad its raw materials and even its labour force, as slaves, in return for the sale of its products.

Against these advantages was set the much-increased danger of war. The new culture had been born in war—the sacking of cities in a state of permanent rivalry. It was difficult to outgrow these habits; defence became a priority; cities were built most inconveniently on hill-tops, like the old high city—Acropolis—of Athens; or on islands, like Tyre; and automatically all citizens had to be soldiers. Nevertheless the small iron age city was both simpler and freer than the old river-valley city. It also gave much greater scope to its citizens, who were forced to organize themselves to look after common interests rather than take their place in a preordained hierarchy. In this way the iron age city gave rise to *politics* and created out of political struggles between the classes in the cities the successive forms of *oligarchy*, *tyranny*, and *democracy*.

Money and debt

One great social invention that provided both for the expansion and the internal instability of iron age civilization was that of metallic *money*—first as stamped bullion in Lydia, and then, after the seventh century B.C., as coin. Metal by weight had been used as currency in the old empires, but its use was exceptional, and barter and payment in kind remained the rule. Money, which soon became the measure of every other value, turned all established social relations into those of buying and selling. Precisely because of its general and anonymous character, money, by bringing rights without obligations,

enabled power to be concentrated in the hands of the rich. At the same time, by superseding the old tribal distribution of real wealth, it took all protection away from the poor. For them the existence of money was negative; they lived in a state of chronic *debt*. True, the oppression of the poor is as old as civilization itself (p. 88). Nevertheless there were real differences between the forms it took in the old civilizations and those in the Iron Age. In the earlier case it was gradual and partial. The economy had arisen directly from a tribal society and tradition was a bar to arbitrary action. The cultivator had many duties, but he also had rights. If he belonged to the land, the land also belonged to him. His payments were in kind and commercial transactions and debts were largely limited to the city population. In the Iron Age there was an abrupt transition from a clan to a money economy. Immemorial customs were destroyed in a few generations and the rule of money could disregard all rights.

On the other hand, the cultivator was potentially far more independent. If he found the situation intolerable he could join a band to form a new colony. If enough people found it intolerable they could and did revolt. With the common use of iron and the training of all citizens in arms these revolts were often successful, and the fear of them kept oligarchs and tyrants in check.

Nevertheless from the beginning of the Iron Age the oppression of money power and the repeated, but inevitably temporary, successes in breaking away from it by reform or revolution becomes the general background theme of city history. Towards the end of the classical age, under the Hellenistic and Roman Empires, money power seemed to triumph absolutely; but its very triumph led to a state of such widespread misery and hopelessness that the whole system broke down and returned to a simpler feudal economy in which money at first played only a small part.

The alphabet and literature

An iron age development of importance for the origin of science was the vulgarization of the elaborate systems of writing—hieroglyphics and cuneiform—of the ancient empires into the common Phœnician *alphabet*, which made *literacy* as cheap and democratic as iron.[2.48] The alphabet arose in relation to trade between people who had different languages

but had to deal with the same things. As its symbolism was based on sound it could be applied to all tongues and at the same time it opened the world of intelligent communication to a far wider circle than that of the priests and officials of the old days. Writing ceased to be confined to official or business documents and a *literature* of poetry, history, and philosophy began to appear. Naturally poetry and prose narratives themselves, in the form of *epics* and *sagas*, must have long preceded alphabetic or even hieroglyphic writing, being handed down by bards or professional story-tellers. It cannot be claimed that an alphabet is an essential to the production of literature, as the example of China shows. Nevertheless, the Chinese achievement was only made possible by the creation of a bureaucratic feudal class who monopolized learning and also largely sterilized it.

4.3—*PHŒNICIANS AND HEBREWS*

The first peoples to profit by the new conditions of iron age civilization were the Phœnicians of the Syrian coast. They were helped by their central position between the old great powers of Egypt and Assyria and by the ample supplies of good ship-building timber from the Lebanon. They led the way in trade, in exploiting sea transport, and in the alphabet, which they invented and popularized wherever they went. But they remained, even in their most distant colonies, such as Carthage or Cadiz, too tied to the continuity of their culture with the old Babylonian civilization to do more than adapt it to the new conditions without generating much that was new, though we may suspect that what advances they did make were either destroyed or misappropriated by the Romans.

The Jews, closely related to them and sharing with them a mixed Egyptian and Babylonian culture, were reserved for a very different role in cultural history. Placed as they were at the very centre of warring peoples, Egyptians, Hittites, Philistines, and Assyrians, followed later by Persians and Greeks, and without the resources of overseas trade, their independence always remained precarious and was only saved in the end as a national entity by the evolution of a cultural tradition or law written in a book—the Bible. They were also, as a small people living in a relatively poor country, able to escape, though only by continuous efforts, from domination by native kings or oligarchs. For both these reasons inde-

pendence, liberty, and democracy became indissolubly associated in their religion. In this the Jews were unique in the ancient world, and the influence of their religion and their sacred books was to prove of enormous importance to the subsequent development of civilization (pp. 182 f., 711 f.).

The Bible: law and righteousness

The Hebrew Bible, or what we call the Old Testament, is far more than a collection of ancient history and legend, invaluable as that is for our understanding of the past. It was first written down about the fifth century B.C. and has been preserved ever since as a religious and national rallying point. It is a book with a moral, full of propaganda expressed as poetry. Propaganda is as old as writing, but hitherto it had been the propaganda of the great and mighty, of the king and the priests. The propaganda of the Bible is different; it is essentially popular, stressing the ideas of *law* and of *righteousness*. Its unique character lay not in each of these ideas separately, because the Jews shared them with other cultures, but in their combination. Righteousness, as we find it in the Bible, is largely a protest against the abuses of the rich and powerful who, then as now, were addicted to falling into foreign ways of oppression. They could be restrained in the name of the law and the covenant with a timely backing of popular violence. The Jews were the first people we know of to fight for an idea and the wars of the Maccabees testified to their fanaticism and militancy. Jewish history is one of continual assertion of the people's right in the name of God. The Bible has, directly in Christianity and indirectly through the Koran in Islam, often served as the inspiration and justification of popular revolutionary movements (pp. 183, 711).

Genesis

It is, however, still another aspect of the Bible, one which is least characteristically Jewish, that has most affected science. The early books of the Bible are versions of old Babylonian and even earlier Sumerian creation stories. They represent an attempt to account for the origin of the world and man, which was an eminently creditable achievement in 3000 B.C., at the very dawn of civilization. These myths, once accepted by the early Hebrew tribes, soon became the essential justification of the covenant between God and His people and therefore beyond

examination and criticism. Later still, because they were part of the sacred books of the Jews, these myths have come down to us as a literal divine revelation to be accepted on faith.

Now the faith of the Jews, both in its original form and in that of a Christianity largely derived from it, survived the break-up of classical civilization because it was solidly based on popular feeling. It was thus far better able to resist the stresses of bad times than the more logical but scarcely more scientific constructions of the Greek philosophers, which were felt to be by the common people, as indeed they were, elaborate justifications of upper-class rule.[2.42a] In the new civilizations, which grew out of the ruins of the old, religion was the central organizing principle, and accordingly the Bible and the Koran gained an absolute authority in matters of science as well as in those of faith and morals. The later chapters of this history will show with what difficulty and how imperfectly human thought has managed to emancipate itself from these fossilized relics of the myths of early man.

4.4—*THE GREEKS*

The most successful in the exploitation of the new conditions of the Iron Age were the Greeks. They had the double advantage of being more removed from the conservative influence of the older civilizations while being able to make extensive use of their traditions. At the same time they were protected in the early formative period of their culture by their poverty, their remoteness, and their sea-power from the far less cultured but more militaristic successors of the old empires—the land forces of the Medes and the Persians.

The fact that the conscious and unbroken thread of history and science comes to us almost entirely from the Greeks is an accident, but only partly an accident. The Greeks were the only people to take over, for the most part almost unconsciously and without acknowledgment, the bulk of the learning that was still available after several centuries of destructive warfare and comparative neglect in the ancient empires of Egypt and Babylonia. But they did far more than this. They took that knowledge and with their own acute interest and intelligence they transformed it into something at the same time simpler, more abstract, and more rational. From the time of the Greeks to the present day that thread of knowledge has never

been broken. It may have been lost at times, but it has always been possible to find it again in time for it to be of use. The learning of the earlier civilizations has affected that of our own only through the Greeks. What we know now of the intellectual achievements of the ancient Egyptians and Babylonians from their own writings was learned too late to affect our civilization directly.

Classical culture

In Greek lands there was built up between the twelfth and sixth centuries B.C. a unified culture which had made an ample digest of existing knowledge and added to it far more of its own. The resulting *classical* culture, as we now call it, enlarged but not seriously modified by that of Alexandria and Rome, has remained the essential corner-stone of our modern world culture. Classical culture was synthetic; it made use of every element of culture which it could find in the countries it occupied and with which it came into contact. It was not, however, a mere continuation of these cultures. It was something definitely new. The characteristics of classical culture that distinguish it are not, however, any of those which are sometimes called cultural. There have been other civilizations, both before and after, that have had as distinctive an art and literature. The great contributions of classical culture were in political institutions, particularly democracy, and in natural science, especially mathematics and astronomy.

The birth of abstract science

The unique character of Greek thought and action resides in just that aspect of their life which we have called the scientific mode. By this I do not mean simply the knowledge or practice of science but the capacity to separate factual and verifiable from emotional and traditional statements. In this characteristic mode we can distinguish two aspects: that of rationality and that of realism; that is, the ability to sustain by argument and the appeal to common experience.

That the Greeks could achieve this, even partially, is due to the historical circumstances in which their culture took shape. The Greeks did not make civilization or even inherit it—they discovered it. The enormous advantage they gained by this was that for them civilization was something new and exciting and could not be taken for granted. The original

culture of the mainland Greeks was of the simple European peasant type. It was unable to stand up against the much more elaborate cultures of the countries the Greeks moved into —that extremely rich and mysterious secondary culture of Crete and Anatolia from which so much of classical culture is derived. Words ending in " issos " and " inthos " seem to be of Cretan origin ; some have passed on to us, as in the names of Narcissus and Hyacinth. The influence on the Greeks of the original centres of civilization, Mesopotamia and Egypt, was not to arise till much later.*

In losing their original culture, however, the Greeks did not and could not take over the cultures of the other countries in their entirety. What they did was to select from foreign cultures what seemed to them to matter. This included in practice every useful technique and in the field of ideas mainly the explanations of the workings of the universe, rejecting the enormously complicated elaboration of theology and superstition that had been built on them in the decadent period before and during the iron age invasions. Homer, the first and greatest of the Greek poets, fixed for all time the picture of the world the Greeks came into. In the *Iliad* and *Odyssey* we find an enormous contrast between the simple peasant life of the newly arrived Hellenic clans and the complex rich and ancient civilizations that they discovered only to destroy. Homer's poems remained as the bible of the Greeks, providing the common basis of belief about gods and men and the arts of peace and war. They contained as much science as the average man ever needed to know.

The economic basis of the Greek city

Greek culture, in common with most of the Western iron age cultures, had such a different economic base from that of the older river-irrigation cultures that much of their way of life was intrinsically unassimilable. It depended on a rather poor kind of dry farming with small peasant holdings helped out by vineyards, olive groves, and fishing. Hesiod, a poet of the early Greek period, describes this life in rather grim terms. His father's land at Ascra in Boeotia he describes as " cold in winter, hot in summer, good at no time." Nevertheless, though liable to periodic debt crises, iron age economy was, until slavery was introduced on a large scale, basically stable. It was supplemented and balanced by extensive foreign trade,

no longer as in the older civilizations mainly in luxurics for temples and palaces, but in bulk commodities for the common citizen.

The most characteristic Greek city state of Attica was so short of good corn-growing land that it depended on its exports of pottery, olive oil, and silver to buy the food for the relatively enormous population of over 300,000 of the city of Athens. The early Greeks were able to exploit their local resources to the full with all the intensity and simplicity that are possible only in a compact city. In these circumstances there were rapid and even violent economic and political changes, while tradition, though never lost, was at a discount. The more enterprising citizens had both the incentive and the ability to think out what they wanted to do and to do it. In the measure that they succeeded they could improve their status in society, held back neither by clan nor by state barriers. Institutions and divinities became less important and more attention was concentrated on men.

Art and dialectic

The realistic representation of man in painting and sculpture, in drama and in science, was the characteristic new feature of Greek civilization. Greek art as represented on statues and vase-paintings—the large frescoes have all been destroyed—shows a concentration on the naked human body that would seem odd if we were not so accustomed to it. It derives originally from ritual games and the cult of athletics that sprang from them. Egyptian statues had a directly magical purpose: they had to re-embody the spirit (Ka) of the dead man, they had to be life-like to work. The Greek sculptor was more sophisticated. He was trying to suggest an ideal to be aimed at in human bodily perfection. In Greek culture the athlete, the artist, and the doctor worked closely together, and this resulted, among other things, in a concern of the medical profession with health rather than disease.

Realism in art went with rationality in words. Because of the fading of ancient sanctions each case had to be argued out on its merits. The history of Greek philosophy and Greek science—the two were never distinguished in those days—is the history of such a sequence of arguments; back-and-forth arguments of the kind that they called a *dialectic*. The capacity to argue was also made possible by the political features of

Greek life. The small city state gave much more scope for the average *individual* citizen than did the capital of a large empire. At the same time the intense political life of the city, with its emphasis on trade deals and lawsuits, in which at first every man was his own lawyer and judges were chosen by lot, made it possible and indeed necessary to develop argumentation to the highest degree. This emphasis on the mastery of words led to a great literature and oratory, but it had the disadvantage of drawing thought away from the study and handling of things.

The separation of science from technique

Greek science has an altogether different character from that of the early civilizations; it is far more rational and *abstract*, but it remained as far or farther removed from technical considerations. Its traditional presentation is in the form of an argument based on general principles, rather than as examples drawn from the particular problems of technique or administration such as we find in Egyptian or Mesopotamian texts (p. 81). Mathematics, especially geometry, was the field which the Greeks esteemed most highly and where their methods of deduction and proof are those we still use. Because of the immense prestige of these methods we are apt to overlook the fact that they are applicable to only a very limited part of Nature, and even there only where the spade-work of observation and experiment has been done. A belief that the universe is rational, and that its details can be deduced from first principles by pure logic, certainly served in the early days of Greek science to liberate men from superstitions. Later, particularly after Aristotle had become an authority instead of, as he wanted to be, an instigator of research, this abstract and *a priori* approach was to prove disastrous to science. It led generations of intelligent people into the belief that they had solved problems which they had not even begun to examine (pp. 218 f., 713).

The technical developments made in the early Iron Age, and especially by the Greeks before the Alexandrian period, though important in their effects, were not innovations as fundamental as those of the Bronze Age. The use of iron led directly to the improvement of all hafted tools such as axes and hammers, and also made possible implements like the *spade* which would have been too expensive in bronze to be of any use. It probably also made possible the use of the *hinge*, leading to two new tools of some importance—the tongs and the drawing compass.

These all arise from the ease with which iron bars may be bent over in a loop and then welded to form a hole for a haft or peg. It was not so much the improvement of the tools as their ready availability that constituted the revolutionary technical advance of the Iron Age. The most important developments came late through the marriage of Greek mathematics and Egyptian or Syrian techniques, including, as we shall see (p. 158), a whole host of applications of rotary motion, mills and presses, pulleys and windlasses, as well as hydraulic and pneumatic devices, water-lifts and pumps.

Of chemical inventions the most important is that of blown glass first made in Egypt, though this remained for long a luxury product. As a result of a few innovations and many improvements, the efficiency of classical techniques, particularly metal-using techniques, was by the sixth century B.C. well above that of the bronze age cultures in their heyday. This was one of the reasons why the Greek armoured soldiers were for a few centuries able to overcome far larger numbers of Asiatic troops.

The technical advances of the Iron Age did not, however, affect the learned in the same way as had those of the early Bronze Age. It was partly because they were essentially improvements and not radical innovations that they did not strike the imagination. Further, they created little demand for new auxiliary scientific techniques. There was enough arithmetic and geometry to cope with them already. The most powerful reason, however, was that the craftsman was still despised. The hand worker, *cheir ourgos* in Greek (our surgeons are still called Mr, not Dr), was considered a definitely inferior being to the brain worker or contemplative thinker. This was no new idea; it was inherited from the old civilization (pp. 78, 88), but it was strongly reinforced, especially in later Greek society, by its association with slavery. Although much craft work was done by free men they were degraded by competition with slaves, so that their work was called base or servile!

In the same way a slave society debased the economic and social position of women. Indeed, the position of the wives and daughters of Greek citizens was far worse than it was in the older civilizations. They were precluded from taking part in public life and were little better than domestic slaves. As a result all domestic work, which included far more arts than it

does now, such as weaving and the preparation of simple remedies, was beneath the concern of the philosopher. For although the philosophers drew on the work of the craftsmen for the derivation of their ideas as to how Nature worked, they had little first-hand acquaintance with it, were not called on to improve it, and consequently they were unable to draw from it that wealth of problems and suggestions that was to create modern science in Renaissance times.

Architecture

There is one important exception to be made to the general contempt for mechanical operation. Architecture in Greek times advanced to the level of a citizen's profession, not of a mere manual art. We all know the triumphs of beauty, proportion, and symmetry of Greek architecture and the impressiveness of the Roman architecture that followed it. Now architecture is pre-eminently an art depending on geometry and involves accurate drawing. It could therefore hardly fail to affect the queen of Greek science, mathematics. Two instruments helped in the same direction, the draughtsman's compass and the lathe. The compass was such a convenient, accurate tool that it is not surprising that Greek geometry tied itself almost exclusively to ruler-and-compass constructions. The pole lathe, with its backward and forward motion, derived from the bow drill, was a bronze age invention; the modern lathe, belt-driven, came only in the fourteenth century A.D.,[2.31] though pole lathes are still in use in many parts of the world, and were in England down to fifty years ago. On the lathe it was possible to turn cylinders, cones, and spheres, and they provided admirable playthings for the mathematician. The degree to which the techniques influenced science in Greece was not negligible, but it was relatively far less than in the older civilizations. Greek science accordingly developed in a more general and independent way but, lacking the check of experience, it was apt to get lost in guesses and abstractions.

Content and method in Greek science

Nevertheless, modern science is directly derived from Greek science, which provided it with an outline, a method, and a language. All the general problems from which modern science grew—the nature of the heavens, or man's body, or the workings of the universe—were formulated by the Greeks.

Unfortunately, they also thought that they had solved them in their own particularly logical, beautiful, and final way. The first task of modern science after the Renaissance was to show that for the most part these solutions were meaningless or wrong. As this process took the best part of 400 years it might be argued that Greek science was a hindrance rather than a help. However, we cannot tell whether, in the absence of Greek science, the problems would have been set at all.

Stages in the development of Greek science

The history of Greek science, though it formed one continuous movement, may conveniently be split into four major phases, which may be called: the Ionian, the Athenian, the Alexandrian or Hellenistic, and the Roman phases. The Ionian phase (4.5) covers the sixth century B.C. and is that of the birth of Greek science in the region where the influence of the older civilizations was most felt. It is associated with the legendary figures of Thales and Pythagoras and other Nature philosophers who speculated, in a most materialistic way, on what the world was made of and how it had come to be. This philosophy, as becomes an age of social development, was essentially positive and hopeful.

The second phase (4.6) covers the years from 480 to 330 B.C., between the successful end of the Persian wars and the effective suppression of the independence of Greek cities by Alexander the Great. It was during this period that Greek culture reached its peak of achievement in the Athenian democracy of the age of Pericles, only to destroy itself in civil strife and war. In this period the interests of philosophy shifted from the explanation of the material world to that of the nature of man and his social duties. This was the great period of Socrates, Plato, and Aristotle, usually considered as the high point of Greek wisdom.

The third phase (4.7) of Greek culture, that called Hellenistic, began with the decadence of the independent city states and their supersession by land empires of a new type. The empire of Alexander brought Greek science once again into direct contact with the older sources of culture in the East as far as India. Alexandria became a new home for science where, for the first time in history, it was subsidized through the founding of the Museum. The result was the great development of mathematics, mechanics, and astronomy that we associate with

Euclid, Archimedes, and Hipparchus. In the history of science, as distinct from philosophy, this third phase was to be the most important of all, for it was then that the body of exact science was first formed as a coherent whole, and enough of it survived despite the losses of the dark ages that followed to set science going again nearly 2,000 years later. From the second century onwards, with the coming of the Romans, this effort slackened and came to a stop long before the actual fall of the Empire. This last phase (4.8) cannot be distinguished by any originality, but as it was to be the bridge between classical and all later science it deserves separate consideration.

4.5—*EARLY GREEK SCIENCE*

Ionian naturalism

Greek science is usually recognized as originating in the Ionian cities of Asia Minor, particularly Miletus, where contact with the ancient civilizations was closest, and in the new colonies of Greeks that had been formed in Italy and Sicily. It appeared in the sixth century B.C., just at the time when the rule of the old landed aristocracy was breaking up and power was being seized by a set of local bosses, the *tyrants*, with the support of the trading classes. The Greek world of the sixth century was one of violent expansion. Its commercial centre was first the eastern Ægean, settled mostly by Ionians, one of the original tribal groups of the mainland Greeks. These set up colonies over the Mediterranean as far as Marseilles, Naples, and Sicily, and east over the coasts of the Black Sea. When Persian pressure drove them from their original homes the colonies in turn became centres of trade and culture of essentially the same character. That is why it is reasonable to include Thales from the mother city Miletus, Heraclitus of near-by Ephesus, Pythagoras a refugee from Samos settling in south Italy, and Empedocles of Sicily all in the group of Ionian philosophers.

In this time and environment tradition was at a discount and new answers to old questions had a chance to be heard. The great value of the early period of Greek thought was that it tried to answer all questions in a simple and concrete way. It was an attempt to formulate a theory of the world—what it is made out of and how it works—in terms of ordinary life and labour.

Philosophers and sages

The people who asked and answered these questions were only later, by Socrates, called *philosophers*, i.e. lovers of wisdom. In their own time they were called sophists, i.e. wise men. We now know very little about them or what they believed; most was handed down by oral tradition and finally a few fragments have been saved by references in the works of Plato and Aristotle, who used them chiefly to refute or make fun of their predecessors. The very fact that they were known and remembered and that legends about their lives have persisted shows how important they must have been in their time. When a new civilization was crystallizing after the warfare of the early Iron Age these philosophers presented a new social type. Nevertheless they were in essence wise men or sages who had picked up and were retailing the old knowledge of the East, adapted and improved on to suit the new times. They were also prophets and leaders of religious mysteries, often founding semi-monastic communities that were also schools. Those that succeeded—and they are the only ones that we hear about—usually managed to secure the position of political or scientific adviser to some tyrant or democratic boss, and were consulted or probably gave gratuitous advice on every kind of subject. If they quarrelled with their patron they were usually snapped up by a rival. It added prestige and stability to a government to have a famous philosopher behind it. Pericles for instance had the benefit of the presence of Anaxagoras, but this time the philosopher went too far in flouting popular beliefs and he had to be dropped. Whether they favoured the democratic or aristocratic side, they were nearly all well-to-do gentlemen. We hear of a few who had to work for a living; Protagoras and other sophists of the fifth century accepted fees for teaching. Plato, who was rich enough not to need to, sneers at them for doing so. They were, he felt, losing their amateur status as philosophers.

It was not only in Greece that such philosophers were to be found. In many parts of the world the disturbances of the Iron Age gave scope to men with similar ideas and messages. In Palestine there were the prophets and the later authors of the Wisdom literature such as Ecclesiastes or the book of Job. Jeremiah may well have met Thales at Naucratis in Egypt. In India there were the rishis and buddhas, of whom Gautama, the Buddha, is the most famous. In China Lao-tze and

Confucius lived at about the same time. All had in common the formulation of general views of the world of Nature and man. Most advised princes and tried to reform States without any lasting success. Most were unorthodox in their time, even when they claimed, as Confucius did, that they were trying to recapture the wisdom of the Ancients. It was only later that they were to become the founders of new orthodoxies.

Their success was due to the fact that they filled the gap in ideas left by the economic transformation of a bronze to an iron age civilization. They provided what Marx called the ideological superstructure for a new system of relations of production. In that new system the direction of society in the hands of merchants, tyrants, and military princes was apparently more divorced from the material side of production than it was in the Bronze Age. Nor did the philosophers, unlike the great directors of works of the time of the canals, pyramids, and temples, have anything to do with the actual material running of the economy. As a result the superstructure they put up was, in general, idealist and inimical to the growth of experimental science.

The early Ionian philosophers do not, however, fit entirely into this picture. In their time the slave State and the rule of the rich were by no means fully established. Accordingly they differed from most of the wise men of the East in that they were at the same time materialistic, rational, and atheistical. They were concerned less with morals and politics and more with Nature than their successors.

The world and its elements: Thales, Heraclitus, and Empedocles

The first of the traditional Greek philosophers was Thales. He is credited with holding the theory that everything was originally water from which earth, air, and living things separated out. This is recognizably the same theory as that of the book of Genesis, a common Sumerian creation myth, reasonable enough for a delta country where the dry land had to be won from the marshes. These myths, because they were faithfully preserved in the original form which dates from before the first class societies, are fundamentally materialist.[2.47] What is new about Thales' version of these is that he left the creator out. Like Laplace centuries later in his answer to Napoleon, "he had no need for that hypothesis." The

materialism of Thales is contained in his interest in Nature and rejection of metaphysical speculation, which was later interposed to justify a class society. It is not a mechanical materialism but rather one in which all matter is thought of as alive. He was a *hylozoist* (matter-life). This basic materialism and atheism was maintained by the later philosophers of the school, Anaximander and Anaximenes, who modified the hypothesis to make it account for more phenomena. They also invoked earth, mist, and fire, as the *elements* (l, m, n) (in Greek—*stoicheia* or letters) out of which the world was made, as words are spelled out of letters. Heraclitus, the philosopher of change, took as his motto *panta rhei*, everything flows. He thought fire was the prime element because it was so active and could transform everything. His expression for this is revealing: " all things are an exchange for fire, and fire for all things, even as wares for gold, and gold for wares." [1.14.16] This reveals once again how technical processes and economic practice engendered the new philosophy. He also introduced the idea of opposites, some things, like flame, tending to move up, and others, like stone, to move down. The two opposites were necessary to each other and generated a tension like the bow and its string. This is the first enunciation of a dialectical philosophy.

Empedocles, the successor of this school of materialist philosophers, demonstrated by experiment that invisible air was also a material substance, and fixed the order of the ancient elements as earth, water, air, and fire, one above the other, each striving if disturbed to get back to its place. He thought that the opposite tendencies, love and hate, which he also conceived as material principles acting mechanically, were continually mixing the elements up and separating them out again. This is similar to but probably quite independent of the Yin and Yang dualism of ancient China. Here also we have two principles, male and female, fire and water, interacting to form the remaining elements, metal, wood, and lastly earth, and from them by further mixtures the " ten thousand things " of the material world.

The whole trend of Ionian thought was towards a dynamic world of *continuous mutual transformation* of *material elements*. Most philosophers of later times tended to concentrate more on the static *natural order* of the elements and to think of them as a fixed and unalterable part of the structure of the universe.

This static order of elements consecrated by Aristotle was used to limit any kind of progressive change, particularly social change. This could be done by equating elements to social classes and inferring that the ideal and final state of the social universe was one in which the lower classes were subordinated to the upper. The identification of the social and natural worlds hindered the understanding of either. It turned an originally materialist theory into a formal one and hindered the development of astronomy, medicine, and chemistry by saddling them with far-fetched analogies which claimed the sanction of a universal order.

Another deep-seated confusion underlay the world view of the Ancients—their elements had to fulfil two incompatible functions. In one aspect they stood as the actual materials and motions of the world as they knew it; they served to explain without any recourse to the gods the whole panorama of land and sea, sunshine and storm. In that sense we still speak of the fury of the elements. In quite another way the elements also stood for qualities—hotness and coldness, wetness and dryness, lightness and heaviness—attributable to anything. Each element was not pinned down to a particular material substance, as were the chemical elements of the nineteenth century. Anaxagoras (*c.* 500–428 B.C.), last of the Ionians, went so far as to say that the seeds of every element were in everything, like our present *states of matter*, gaseous, liquid, and solid.

The triumph of the original Ionian school was that it had set up a picture of how the universe had come into being and how it worked without the intervention of gods or design. Its basic weakness was its vagueness and purely descriptive and qualitative character. By itself it could lead nowhere; nothing concrete could be done with it. What was needed was the introduction of *number* and *quantity* into philosophy.

Quantity and number: Pythagoras

The tendency to associate arbitrary simple number ratios with celestial objects, which may well have had its origins in Babylonian astronomy, already appeared in the work of Anaximander (611–547 B.C.), who put the distances of the stars, moon, and sun at nine, eighteen, and twenty-seven times respectively the thickness of the earth disc. The attribution of *numbers* to all aspects of Nature is associated with the doctrines

of Pythagoras (582–500 B.C.). He came from Samos, an island near Miletus, but emigrated to south Italy, where he founded a kind of philosophic, religious school. Whether Pythagoras was an entirely legendary figure or not, the school that bore his name was real enough and was to have an enormous influence in later times, particularly through its most important exponent, Plato (427–347 B.C.).

Two trends of ideas are blended in Pythagorean teaching, the *mathematical* and the *mystical*. It is doubtful how much of the Pythagorean mathematics was his own. Certainly his famous theorem on the right-angled triangle had been well known as a practical rule to Egyptians, and the Babylonians made long tables of "Pythagorean" triangles. It may even be that the whole of Pythagorean number theories, in their mystical as well as their mathematical aspect, are drawn from some source in Eastern thought, as their character strongly suggests. But whether Pythagoras was an originator or a transmitter, the connection set up by his school between mathematics, science, and philosophy was never again lost.

Pythagoras saw in *numbers* the key to understanding the universe. He related them on the one side to geometry, showing how squares and triangles could be made of appropriately arranged points, and on the other to physics with the discovery that strings which were in simple *ratios* of length emitted notes with regular musical intervals—octaves, thirds, etc.—between them. This linked the previously sensuously appreciated *harmony* with ratios of numbers and hence with geometrical forms. The Pythagoreans set the whole tone of Greek geometry by their insistence on the cosmic importance of the five regular solids whose sides could be made from triangles, squares, and pentagons. The pentagon was particularly magical because its construction with ruler and compass was a mathematical triumph. Two of the Platonic solids, the dodecahedron and the icosahedron, have pentagonal symmetry. Euclid's whole geometrical synthesis indeed leads up to the method of construction of these two solids; and the proof that there can be no more was a culminating point of Greek geometry, foreshadowing the modern theory of groups.

Ratio and irrationals

One fundamental mathematical discovery came from the Pythagorean school, though probably some time after the death

of the master. If every measure of length can be expressed by a number, the *proportion* between two different measures should be expressible as the *ratio* of two numbers. But a very simple case shows that this cannot be done. Whatever number you use to express the length of the sides of a square, that of its diagonal cannot be expressed as another number, whole or fractional. This is equivalent to saying that no fraction multiplied by itself can give exactly 2, or that $\sqrt{2}$ is *irrational.* The discovery that there were irrational numbers was a serious shock to the whole Pythagorean school and contributed to its break-up. One way out was to say that measures were unreal; the other, that finally adopted, was to extend the concept of numbers to include irrationals.[2.41]

It is to the Pythagoreans that we owe the importance of the circle and the sphere in astronomy. They thought that earth was a sphere and further that it moved together with the planets—the sun, moon, and a mysterious counter-earth—round a permanently invisible central fire. This idea, when rationalized by Heraclides (375 B.C.) and Aristarchus (*c.* 310–230 B.C.), was to lead to the modern picture of the solar system.

The work of the Pythagorean school is the very foundation of mathematics as well as of the physical sciences. Even in mathematics the mystical element is very much in evidence. The Pythagoreans linked the eternal soul with the eternal forms of number, attributing it particularly to the number $10 = 1 + 2 + 3 + 4$. The whole world, according to them, was made of pure numbers. This form of extreme idealism is linked with cabbalistic number magic, still invoked in the blessed trinity, the four evangelists, the seven deadly sins, and the number of the beast. It is also apparent in modern mathematical physics whenever its adepts try to make God the supreme mathematician.

Mysticism enters science

In physics also the Pythagoreans ran too much beyond the facts, and substituted number mysticism for experimental knowledge. The mystical side of Pythagoreanism links it with the Orphic mysteries, a relic of old community magic that had already become a means of escape from the harsh realities of the Iron Age.[2.45.154] Orphism as a slave religion has indeed some points of resemblance to Christianity, especially in its symbolism of the wheel and the cave.[8.67] The main thesis of

the Pythagoreans was the doctrine of the transmigration of souls, essentially the same as that of the Hindus, though possibly quite independent of Indian influence. The object of the cult is to escape from the cycle of reincarnation by common mystical experiences, "*orgies*," and ecstatic mystical contemplation, "*theories*" = visions.[2.17.38] This is similar to the idea of the attainment of Nirvana through Yoga which Gautama tried vainly to resist. The idea of rebirth was not unreasonable in the Old Stone Age, where it first appeared. In the Iron Age it was essentially reactionary because it removes all meaning from social injustice and war, and wins for them at least a tacit approval (p. 711).[2.13] In the *Bhagavad Gita*, when Arjuna asks in horror how fratricidal strife came about, Krishna answers:

> If the red slayer thinks he slays
> And that the slain thinks he is slain,
> They little know the hidden ways,
> I turn, I pass, I come again.

The mystic aim was the achieving of detachment through purification. This purification was originally a purely magical initiation ceremony or rebirth. It later acquired a link with alchemy through the purification of metals by fire (p. 86). The Pythagoreans introduced the idea of purification through knowledge, the *pure knowledge* of passive *contemplation*. This view, as expressed by Plato, was that the people, like spectators at the games, can be divided into three classes: those who go to buy and sell, the competitors, and the spectators. The last, who merely contemplate, he deems far superior. This ideal of pure science as contemplation, drawn from a primitive ritual debased by class society, has lasted down to our time. Now, as then, it provides a convenient excuse for enjoying knowledge without responsibility.

Though these consequences of Pythagorean views are clearly reactionary they come from an age later than that of Pythagoras himself. The original Pythagorean community, according to Thomson,[8.67] was as much political as religious, and as such was persecuted and finally dispersed. He regards Pythagoreanism as the first expression of *democratic* thought, that is of the rationalism of the merchant *middle* classes as against the traditionalism of the landed aristocracy, and compares its influence with that of Calvinism. In particular he links the Pythagorean insistence on the value of the *mean* and of harmony with the solution of the political struggle through

the rise of the merchants, an idea which we now associate with Aristotle.

The influence of Pythagoras

The school of Pythagoras marked a branch point in the development of a Greek science both in theory and practice. From it stem two very different systems of thought. The most abstract and logical aspects were taken up by Parmenides and, mixed with much mysticism, became the basis of Plato's idealism. In the opposite direction Pythagoras' number theory was given a materialist content in the atomic theory of Leucippus of Miletus, 475 B.C., and Democritus of Abdera, 420 B.C.

In practical science the Pythagoreans established the possibility of dealing with physical quantities by reducing them to measure and number, a general method which, though often stretched beyond its proper limits, was to provide one continuous means of expanding the control of man over Nature. For mathematics the importance of Pythagoras was even greater in that his school established the method of *proof* by *deductive* reasoning from *postulates*. This is the most powerful way of *generalizing* experience, as it transforms a number of instances into a *theorem*.* Valuable as it is in mathematics, deductive proof has been used ever since in the service of idealism to prove palpable nonsense from self-evident principles.

Parmenides

Among the first philosophers to do this were Parmenides (470 B.C.) of Elea in south Italy and his pupil Zeno (450 B.C.), both connected with the aristocratic and conservative party in the city. Parmenides was the philosopher of pure reason. He violently attacked the whole of observational and experimental science, claiming that such studies could only give uncertain opinions owing to the fallibility of the senses, while the truths of number appreciated by pure reason were absolute. The demand for *absolute truth* and certainty, not to be found in the fallible senses, in "the blind eye, the echoing ear," expresses the deep need for fixity that always recurs, usually on the losing side, in times of trouble.

It is not surprising that this anti-scientific idealistic trend was later taken by Plato and has persisted in philosophy to this day. Parmenides went further; he refuted, by appealing to logic, Heraclitus' view that everything changes. If *what is, is* and

what is not, is not, nothing can ever happen, and *change is impossible.* Not only change but also variety is impossible in such a universe. The *real* universe is one and changeless. As our senses show us variety and change they must be only seeming, and the apparent material world must be an *illusion.* This is the first clear statement of the extreme idealistic view, and the beginning of *formal logic.* Hegel took up Parmenides' logic, and refuted his proofs by claiming that the idea of being contradicted by the idea of not being gives rise to the idea of becoming, and thence by the same *dialectic idealism* to the whole complex ideal world. This was the philosophy which Marx turned on to its feet in founding *dialectic materialism.* Parmenides' idealism was not so pure as it seemed. The idea of changeless unity is an extremely convenient one for a minority ruling by " divine " right.

Parmenides' pupil, Zeno, attacked the basis of Pythagoras' mathematical and physical theory by producing four ingenious paradoxes which appear to prove logically that time or distance can neither be continuous nor discontinuous. If space is continuous the runner can never reach the goal. If he is halfway it will take him time to get half the rest of the way and so on *ad infinitum.* If space is discontinuous the arrow can never move because it is either at one point or the next and there is nothing between. Zeno's paradoxes were not entirely useless—they are the beginning of the search for *rigour* in mathematics. These subtleties were taken to prove that the visible world cannot really exist; but they may serve as well to show that pure reason can be sillier and emptier than anything the senses can contrive.

Atoms and the void: Democritus

The most effective answer to these idealist tendencies was given by Democritus, whose *atomic theory* was to have such an enormous influence on later science. Instead of thinking of a universe of ideal numbers he imagined one made out of small innumerable uncuttable (a-tomos) particles, *atoms* moving in the *void* of empty space. The atoms were unalterable, to this degree agreeing with the changelessness of Parmenides; they were of various geometrical forms, to explain their capacity for combining to form all the different things in the world; and their *movement* accounted for all visible change. Thus Democritus was able to include the mathematical content of

Pythagoras, especially the insistence on the importance of geometrical form, while rejecting its idealism and mysticism.

The introduction of the void—nothingness—into philosophy was also a daring step. The universe of the older philosophers was that of common sense; it was a full universe, a plenum. The idea of a *vacuum* was abhorred by all reputable philosophers, and the abhorrence was fathered on to Nature. Many of the great achievements of Renaissance physics, like Galileo's dynamics, and later scientific and technical developments, such as the laws of gases and the steam-engine, arose in the process of overthrowing this idea (pp. 329 f.).

The atomic theory had from the start a radical political flavour because it was frankly materialistic and avoided appeal to preordained harmonies. The authority of Plato and Aristotle, who supported doctrines of ideals or substantial forms (p. 146), was sufficient to prevent its general acceptance. Nevertheless it remained throughout the classical period as a persistent heresy, and through Epicurus and Lucretius had an effect on philosophy and ethics in its later stages. It stood for a world which maintained itself through the natural working of its parts and needed no divine guidance. The atomism of Democritus was completely deterministic, but later Epicurus introduced a certain amount of original variation or bias to his atoms in order to allow for variety and for free will in man.[2.33]

It would be a mistake to think of Greek atomism as essentially a scientific theory of physics. No conclusions were drawn from it which could be practically verified. Nevertheless, it was the lineal and acknowledged ancestor of all modern atomic theories. Gassendi (p. 329), the first of the modern atomists, drew his ideas straight from Democritus and Epicurus. Newton (p. 327) in his turn was a fervent atomist, and it was the inspiration of his work that finally led John Dalton (p. 452) to found the atomic theory of chemistry. The atoms of chemistry have not proved as uncuttable as their name implies, but the deeper explanations of nuclear physics still lies in the same atomic tradition.

The age of Pericles

The city of Athens emerged at the end of the Persian wars in 479 B.C. as the economic and cultural leader of the Greek world. It had earned that place by its courage and persistence in opposing the invader. Its success was, in fact, largely due to

the use to which it put the money drawn from the Laurion silver mines. On Themistocles' advice it went to build up a navy which, manned by the poorer citizens, ensured not only victory for the city but also the power of the common people in its government. The commercial leadership of Athens still further increased its wealth and drew to the city not only artists and sculptors but also historians and philosophers. For the next century, even after the disastrous war with Sparta, Athens was the intellectual centre of the Greek world; and the heritage of Ionian science, particularly the mathematical, astronomical Pythagorean tradition, there received a new impetus.

The period is one of enormous importance to the development of world science because it furnishes the link between the poetic speculations of the Ionians and the precise calculations of the Alexandrian period. Indeed, the last of the Ionian philosophers, Anaxagoras of Clazomenæ, settled in Athens, was the friend of Pericles, and was, as has been told, expelled for rationalism in 432 B.C.

It was in this period that the major problems of science, social as well as natural, were set, though many diverse solutions to them were to be proposed in succeeding centuries. From then on Greek science was to be autonomous and to develop its own particular character within its own, largely unrealized, limitations. In the natural sciences this was an emphasis on mathematics and astronomy as providing tests of truth and, on a lower level, on medicine as a means of preserving health and beauty.

The triumph of geometry

From the moment of the discovery of the irrational (p. 124), Greek mathematicians turned away from numbers to the consideration of lines and areas, in which such logical difficulties did not arise. The result was the development of a *geometry* of measurement which is perhaps the chief gift of the Greeks to science. Babylonian mathematics and its success in India and Islam remained primarily arithmetical and algebraic. The chief architects of this transformation were Hippocrates of Chios, *c.* 450 B.C., and Eudoxus, 408–355 B.C. The former was the first to teach in Athens for money and the first to use letters to denote geometrical figures. He occupied himself with the geometrical solution to the classical problems of squaring the

circle and doubling the cube. Though he failed in both, he established chains of valuable propositions in the way in which Euclid was later to build his Elements. These problems, together with that of the trisection of an angle, which cannot be solved by ruler and compass, led other geometers like Hippias of Elis to construct higher curves and open a new branch of geometry.

Eudoxus was probably the greatest of Greek mathematicians. It was he who founded the theory of proportions applicable to all magnitudes and discovered the method of exhaustion or successive approximation for measuring lines and areas which after it had been extended by Archimedes was to be the basis of the infinitesimal calculus.

Spherical astronomy

In the same period came the logical development of Pythagoras' world picture. Here the master was the same Eudoxus, as great an astronomer as he was a mathematician. He was able to explain the motions of the sun, moon, and planets by means of sets of concentric spheres each rotating about an axis fixed in the one outside it. The model was crude and mechanical but could serve at the same time in the form of actual metal spheres as a method of observation far more flexible than the old gnomon or dial. It is one from which all astronomical instruments to this day are derived. The theory of spheres was simple, too simple indeed to explain even the facts known long before to the Babylonians, such as the shorter length of the seasons of Autumn and Winter, which take up 89 days 19 hours and 89 days 1 hour respectively compared to Spring and Summer, which are 92 days 20 hours and 93 days 14 hours respectively. At the time these seemed minor blemishes to be removed by adding more celestial clockwork—a process which went on generating complexity until it was all swept away by Copernicus and Newton.*

Greek medicine: Hippocrates

Greek medicine furnished yet another contribution to a coherent scientific world picture. It wove the two strands, one empiric, one philosophic, that have run through medicine ever since. Greek medicine, like Greek mathematics, is in unbroken continuity with the medicine of the ancient civilizations (pp. 84 f.). The Greek doctors seem to have belonged

to the Asclepiadae, or clan of Asclepias, the demi-god of Medicine, one of the occupational clans or guilds. Indeed we have still in the Hippocratic oath [2.46.332] a well-preserved relic of an adoption ceremony into the clan, carrying with it certain obligations to clan members and their families, which are still observed today. For instance, we find in it the clause:

> I will impart it by precept, by lecture and by all other manner of teaching, not only to my own sons but also to the sons of him who has taught me, and to disciples bound by covenant and oath according to the law of the physicians, but to none other.[1.40.213]

In Greece, as in the old civilizations, the doctor was somewhat of an aristocrat, dealing mainly with wealthy patrons. The treatment of ordinary people remained in the hands of the old wives and charlatans using traditional and magical remedies.

The first trend in Greek medicine is that associated with the almost legendary physician—Hippocrates of Cos. The so-called Hippocratic corpus is a mass of medical treatises, probably written over the period from 450 to 350 B.C., the tone of which is resolutely clinical. Medicine is treated as the art—*technè*—of curing patients. The most famous quotation from Hippocrates was occasioned by the need to warn physicians not to feed patients suffering from fevers:

> Life is short, and the Art long; the opportunity fleeting; experiment dangerous, and judgment difficult. Yet we must be prepared not only to do our duty ourselves, but also patient, attendants, and external circumstances must co-operate.[1.40.229]

Each case is considered on its merits, but the opinion on it is based on observations of similar cases. In this it follows the tradition of the Egyptian doctors (p. 84). Magical or religious causes or cures for disease are not mentioned, and Hippocrates goes further in an explicit renunciation of such causes. Thus in the passage on the "sacred" disease, epilepsy, we find:

> It seems to me that the disease called sacred is no more divine than any other. It has a natural cause, just as other diseases have. Men think it divine because they do not understand it. . . . In Nature all things are alike in this, that they can all be traced to preceding causes.[1.39.4]

The school of Cos is, moreover, equally intolerant of the application of philosophy to medicine. In *Ancient Medicine* (the author of which may be the sophist Protagoras) we find:

> All who attempt to discuss the art of healing on the basis of a postulate—heat, cold, moisture, dryness, or anything else they fancy—thus narrowing down the causes of disease and death among men to one or two postulates, are not only obviously wrong, but are especially to be blamed because they are wrong in what is an art or technique (*technê*), and one moreover which all men use at the crises of life, highly honouring the practitioners and craftsmen in this art, if they are good.[2.17.63]

Despite this denunciation, the use of philosophical postulates tended to increase in medicine and even to find its way into Hippocratic writings.

In part this arose from the beginning of anatomical and physiological studies. A follower of Pythagoras—Alcmaeon for instance—learned by dissection something of the function of nerves and dared to assert that the brain, instead of the heart, was the organ of sensation and movement. This fact, which must have been known practically to primitive hunters, was still being stoutly denied by doctors 2,000 years later. The more mystical doctrines found much more ready acceptance. Another Pythagorean, Philolaus, formulated the doctrine of the three spirits or souls of man: the vegetative spirits, which he shares with all growing things, situated in the navel; the animal spirit, shared with beasts only, which gives sensation and movement, in the heart; and the rational spirit, possessed only by man and located in the brain. These spirits were to haunt physiology and anatomy for centuries and prevent men using the evidence of their senses, till Harvey laid them to rest (pp. 301 f.).

The doctrine of the humours

The most persistent and damaging to the practice and theory of medicine was, however, the doctrine of the four humours, which was first clearly put forward by Empedocles (p. 121). He was a doctor as well as a philosopher and he naturally extended his cosmological ideas into his medical theory. He considered that the same four elements, or " roots of things," of which the universe is made, must be found in man and in all animate beings. For him, following probably more ancient

and mythical models, man was a microcosm—a small world modelling in himself the macrocosm, the great world. The four elements of the world—fire, air, water, and earth—were matched by the four humours of the body—blood, bile, phlegm, and black bile. These are also the four sacred colours of alchemy—red, yellow, white, and black. According to which was predominant, the man was sanguine, choleric, phlegmatic, or melancholic. This led to a whole system of apparently rational medicine, which was for centuries to supersede the practical art of medicine of the original Hippocratic school (pp. 201, 272, 403). On this theory treatment was aimed at restoring the appropriate balance of the elements by controlling the two opposite pairs of qualities, hot and cold, wet and dry, which determined the elements. Fire was hot and dry, air hot and wet, water cold and wet, earth cold and dry. If a man had a fever he needed more cold, if a chill more heat.

It is easy to see now that these theories bore practically no relation to the facts of physiology, and that medical practice based on them could rarely if ever have good effect. Unfortunately, in spite of their careful clinical studies, the school of Cos were also in no position to prescribe effective treatment. They excelled in prognosis and relied on the patient, if not given violent or unsuitable treatment, getting well through the curative power of Nature. Accordingly the profession naturally preferred a doctrine in which they had a larger share in the cure, and which exalted their art into a philosophy worthy of being followed by the best people.

4.6—*THE ATHENIAN ACHIEVEMENT*

The social philosophy of Athens

In the second and central period of Greek thought the interest of philosophy, which still included science, shifted from the material to the ideal plane. In this it reflected the later stages of the dramatic culmination of the development of the city state in the Athenian empire in the fifth and fourth centuries B.C.[2.45] These events, because they revealed new forces at work in society and because they were so clearly and beautifully set down for future generations in the works of historians like Thucydides, remain of enormous importance to science and politics to this day. It began with the rise, for the first time in human history, of a deliberately constituted citizen

democracy. That democracy remained in power for long enough to show something of its enormous creative possibilities, to which the Parthenon and the Athenian tragedies still stand witness. It fell in the end because it was based on slavery and the exploitation of foreign territory. It was unable to resist the attacks of aristocratic reaction, embodied in the far more primitive State of Sparta well supported by Persian gold.

The failure of Athenian democracy marked the turning point of classical civilization. Never again was it to approach as close to a popular control of social life and the overthrowing of the rule of the wealthy. From then on the Greek city state, for all its material successes and even its intellectual achievements, was doomed to ultimate destruction. Democracy had come near to offering real escape from the economic contradiction of the iron age city; without it the only other path was towards an increase of slavery at home and military adventures abroad. For another five centuries this was to spread Greek civilization over a large part of the world, but its inner development had come to an end.

The philosophers of reaction

The great triad of Greek philosophers, Socrates, Plato, and Aristotle, all belong to Athens, but to the Athens of decline. They drew their enormous ability and power to influence thought from the revolutionary greatness of the first free city; the service they put it to was that of counter-revolution. Socrates, at least as Plato represented him, Plato himself, and Aristotle all showed a scorn of democracy that only partially hid their deep fear of it. Marx was too kind to the philosophers, or perhaps he was thinking of his old favourite Epicurus, when he said: "The philosophers have hitherto only tried to understand the world, the task, however, is to change it." The task that Plato quite consciously set himself was that of *preventing the world from changing*—at least in the direction of democracy.

Socrates and logic

This idealistic reaction in Greek thought was expressed in terms of the new technique of *logic* or the handling of words = logoi. Athenian politics in the democratic era gave to disputation and oratory an even greater importance than they had in most Greek cities (p. 114); they were a recognized way to fame and wealth. This gave rise to a new interest in words and their

meanings. The control of people by words became more rewarding than the control of things by work. A whole new class of professional wise men—the sophists—arrived to teach this road to success to those who were willing to pay. The most famous of them, Protagoras, is remembered for the saying, "Man is the measure of all things," expressing the primacy of human convention over any absolute knowledge. His opponent was Socrates himself, who developed a method of argument in which, by asking a series of questions directed at his opponent's own knowledge, he could in a very short time make it clear to the audience that his opponent did not know what he was talking about. For Socrates the chief end of man was individual goodness or virtue which was to be an automatic result of knowledge. Both the Greek word for goodness, *arete*, and the Latin, *virtus*, originally referred to combative manliness. Ares was the god of war. It took a long time to soften into the ideal of citizenship and still longer to Christian submissiveness. According to Socrates the knowledge which led to goodness was not physical knowledge or indeed anything that could be learned, it was rather a rejection of all *opinion* and reliance on inner *intuition*. In this he resembled his contemporary the Chinese philosopher Lao-tze, who was as sceptical of convention and as secure in the hold on an inner natural truth.

Socrates had his private "daemon" who inspired him at critical moments. What his own beliefs were it is difficult to say, because he wrote nothing and nearly everything we know of him comes from Plato. Socrates was a wonderful talker and a great character and had an enormous influence on the Athens of his day, making both devoted friends and bitter enemies.

Although himself a man of the people he was not a supporter of democracy, and mingled, at least in his later years, mainly with the rich and with aristocratic young men. Some of these, like Alcibiades, turned against the city in the Spartan war, while others, like Critias and Charmides, took part in the reactionary government of the thirty tyrants formed after the defeat. These were turned out by a popular revolt in 403 B.C. and replaced by a democracy which, however, was pledged to the Spartans not to take political reprisals. It was under this government that Socrates was accused of impiety and of corruption of the youth, but the real reasons for his trial were political. His enemies apparently only wanted to exile him, but his calm and defiant defence led them to sentence him to death and

make him the first and most famous martyr of philosophy. The circumstances of his life and death, more even than his own character, mark a parting of the ways in Greek thought. Henceforth philosophy will have a moral or ethical and a natural or physical branch, and for 2,000 years the first will have the greater prestige.

Plato

Plato, as a wealthy young Athenian aristocrat, came under the influence of Socrates at a time when his political ambitions seemed thwarted for good by the return of democracy.[2.5] He determined to devote his life to philosophy with the object of leading men to a better life by working out the principles of a perfect State. This led him on the path of *idealism* in philosophy, and indeed he became for all time its greatest exponent. For though he was far from being the first idealist, he was able to present his views in the form of dialogues with a beauty and persuasiveness that have never been bettered in philosophic writings. Indeed their beauty of expression has hindered men in all ages from seeing the ugliness of the ideas expressed. The main political objective of Plato, expressed especially in *The Republic* and *The Laws*, is to draw up the constitution of a State where all the old privileges of the *aristocracy*—the best people—will be preserved for ever, and which at the same time can be made acceptable to the lower orders. For inspiration he turned to Sparta, where the barrack life the citizens led in common was supposed to preserve them from graft and political intrigue, and to keep down the helots,[2.48] though it had notoriously failed to do the first and ultimately the second as well. Plato divided the citizens of his Republic into four grades: the guardians; the philosophers, who ruled; the soldiers, who defended; and the people, who did all the work. The guardians held everything in common without even family life. The common people were allowed this luxury but no power at all. These class divisions were to be permanent and justified by a myth or "noble lie" about God creating men of four kinds—gold, silver, brass, and iron.

These are the four colours yellow, white, red, and black that already appear in the humours (p. 133), and are also the *varna* of the original castes of India: Brahmins (sages); Kshatryas (warriors); Vaishnavas (cultivators); and Sudras (outcastes). Cornford, however, claims that Plato was not thinking in class

terms and that each class was chosen so as to be most suitable for its duties. However, the passage he quotes hardly bears this out. In Plato's allegory,

> if the rulers find a child of their own whose metal is alloyed with iron or brass, " they must, without the least pity, assign him the station proper to his nature, and thrust him out among the craftsmen and farmers. If, on the contrary, these classes produce a child with gold or silver in his composition, they will promote him, according to his value, to be a Guardian." [2.12.133]

This shows clearly that normally the classes were hereditary but that Plato, like the British ruling class of today, was clever enough to see that to allow a limited number of able members of the lower orders into the upper classes was the safest method of perpetuating their rule.

Through this rigid class system Plato hoped to find perfect and above all stable government. The guardians would have no responsibility to their families but only to the State, and no material cares or ambitions. They would also be subjected to an education in philosophy, mathematics, and music, which would, he thought, induce a superior benevolence. In this way he hoped to graft on to the Spartan constitution some of the remembered glories of the Athens of Pericles, where for some years the new democracy had entrusted the rule of the city to a cultured group of wealthy citizens. Plato hoped to get his political views accepted by finding a prince who was a philosopher or who could be trained to be one. His last effort was with Dionysius the younger, tyrant of Syracuse, but neither he nor his court could stand the rigours of the mathematical training required. Plato's republic has been variously judged by later generations. In the Middle Ages, compared with the arbitrary and inefficient rule of illiterate kings and nobles, it seemed a progressive ideal, especially as it was presented in such beautiful and persuasive prose. In our time, however, we see in it most unpleasant anticipations of the maintenance of the class rule of the capitalists,[2.40] which found an echo in the bogus Corporate State of the Fascists.

To support this central theme of the ideal city, and at the same time to justify the life of its philosopher guardians, Plato took over the views of Pythagoras and Parmenides (p. 126) which exalted the apprehension of absolute truths that were

unchanging, logical, and mathematical. The emphasis on the discussion of words and their true meanings tended to give to words a reality independent of the things and actions to which they referred. Because there is a word for beauty, beauty itself must be real. Indeed it must be more real than any beautiful thing. This is because no beautiful thing is altogether beautiful, and so whether it is beautiful or not is a matter of opinion, whereas beauty contains nothing but itself and must exist independently of anything in this changing and imperfect material world. The same logic applies to concrete things: a stone in general must be more real than any particular stone.

Platonic idealism

Thus grew up the fantastic world of *ideals*—images of perfection—of which the material world was but a flickering shadow on the walls of the cave in which we are imprisoned in this life.[2.38]

Plato moreover was not really concerned with providing an explanation of these appearances; what seemed all-important to him was to prove that certain abstract conceptions were absolute and eternal, independent of sense impressions and to be grasped only by the eye of the soul. These were the triad of absolute values: truth, goodness, and beauty. The first he owed to Parmenides, the second to Socrates, and the third was his own special contribution, though one drawn from the art-for-art's-sake æstheticism of the wealthy Athens of his young days. These absolute *values* are still with us. The claim that they are superior to, and beyond any knowledge derived from, the senses is used now as then to put a limit on scientific investigation and to support intuitive, mystical, and reactionary views.

Yet Plato himself argued for them on the basis of such science as was known in his day. He derived them, in fact, largely from mathematics and from astronomy, or rather astrology. The word *astrology* or reasoning (*logos*) about the stars was coined by Plato himself to replace the old astronomy, or mere ordering (*nomos*) of the stars. Later astrology got such a bad name that the old word came back. He embraced and extended the mystical views of Pythagoras on the cosmic importance of number and geometrical figures, and found in them examples of absolute truth independent of the senses. Plato does not

seem to have contributed much to mathematics himself, but his influence undoubtedly gave it a prestige that drew many good minds to it later. Being, however, deliberately abstract and contemplative, it drew mathematics away from its origin in, and application to, practical experience and thus held back the development of algebra and dynamics.

Astrology

With mathematics Plato coupled astronomy, but it was a peculiar kind of astronomy, the stars as they should be rather than as they were. The old popular view was that the heavenly bodies, and particularly the sun, moon, and planets, were divine beings. That is why old-fashioned people resented as impious the claims of the Ionian philosophers that they were globes of fire wandering (*planein*) through the sky. Plato saved the situation, but at a terrible cost to science: he combined mathematics with theology by asserting, in the face of evidence already existing,[2.17a.77] that the planets showed their divinity by the unchanging regularity of their perfect and circular movements, composing between them the inaudible harmony of the spheres. Thus any alteration was banished from the heavens as he would have liked to have banished it from human affairs, and the highest duty of man was to contemplate eternity and to find in it the proof of his own immortality. Plato's philosophy took back the challenge science had offered to faith. By postulating celestial perfection he stifled the ideas, already expressed by the Pythagoreans, that it was the earth itself that moved. His influence was consequently effective, together with that of his great rival and successor, Aristotle, in holding back man's knowledge of the real motion of the heavens, and with it any possibility of valid physics, for 2,000 years.

The Academy

When Plato's hopes of the philosopher prince faded, he returned to Athens, being captured and nearly sold as a slave on the way. There for forty years (387–347 B.C.) he expounded his doctrines in the groves of the hero Academus to a number of very select pupils. Over the gate was written "Let no one ignorant of mathematics enter here." The teaching in the Academy did not stop with Plato's death. Though it did not develop his ideas significantly it preserved them and, with the prestige of Plato and Athens behind it, the Academy endured

for nearly 1,000 years till Justinian closed it in A.D. 525. It was an extension and rationalization of the mystical fellowship of Pythagoras. Both discussion between initiates and the teaching of aspirants were undertaken. Its great importance is that it is the parent of all the universities and scientific societies of our day. It was Plato himself who determined the character and tone of the institution. It was certainly academic in the modern sense. Pure knowledge, almost exclusively mathematics, astronomy, and music, was to be acquired by the reading of texts rather than the study of Nature, which was full of deceptions and irregularities. Plato's insistence on mathematics, however, did secure the presence of at least one scientific discipline in what might otherwise have been a purely literary education. Confucius, whose influence on Chinese education was to last almost as long as Plato's on that of the West, omitted mathematics. This may well have contributed to the relative backwardness of Chinese science. Ideally, in the Athenian Academy the knowledge of the true, the good, and the beautiful was sought for its own sake. Actually it was considered by the later Greeks, and the Romans after them, that it was an excellent training for a distinguished career for young men of good family.

Platonism

The influence of Plato, however, penetrated much further than the Academy. Progressively debased by keeping the mystical elements and neglecting the logical and mathematical ones, Platonism permeated all conformist thought in late classical times. It mixed early with Christianity and indeed formed the major intellectual support for its theology. After the closing of the Academy Plato's original works were forgotten, all except the most absurd of them, the *Timaeus*, which contains his mythical account of the formation of the world. His teaching was transmitted largely through the Neoplatonism of the even more mystical Plotinus (p. 167). The Arabs rediscovered some of his other works and translated them, but it was not till the Renaissance that they were again studied in the original and had an effect at least as great as when they were first written. It was largely owing to Plato that the early humanists were not scientific. In the sixteenth and seventeenth centuries, however, the mathematical inspiration of Plato played an important part in guiding the thoughts of Kepler,

Galileo (pp. 295 f.), and through the Cambridge Platonists, also of Newton (p. 338).

Aristotle

Aristotle, at first a disciple of Plato, broke from the Academy after the master's death and in 335 B.C. founded a rival school of philosophy, the Lyceum. He was born at Stagira in Thrace, but belonged to the Greek clan of Asclepiadae or physicians (p. 131). Aristotle came to occupy, for a variety of reasons, a central place in the history of science. Living as he did at the culmination of one phase in Greek political life and at the beginning of another, he was in a position to collect all the knowledge of the free Greek cities and pass it on to be applied in the empires that took them over. For most of his life he enjoyed special favours from cities and kings, and he made full use of his opportunities. His scientific output was larger and covered a wider range than that of any other single man before or since. Further, most of his work reached posterity, for it was handed on, enlarged with voluminous commentaries, by the Lyceum, which was at first as active in inquiry as the Academy in contemplation.

Aristotle was a logician and a scientist rather than a moral philosopher. He lacked the high-minded reforming zeal of Socrates or Plato. Belonging to a later generation he realized that Plato's social ideas were out of date. Plato's philosopher prince, Dionysius the younger of Syracuse, was neither able nor willing to preserve the kind of independent aristocratic republic of which he dreamed. Aristotle had his own philosopher prince, no less a one than the young Alexander, whose tutor he was from 343 to 340 B.C., but he was dreaming of carving out a great Macedonian military empire rather than of ruling a Greek city state.

Aristotle was content to make the best of things as they were. He was above all the philosopher of common sense, almost of commonplace. He saw no need to change the State. All that was necessary was for people to adopt a moderate course and things could go on very well as they were. This was the celebrated doctrine of the *mean*—neither too much nor too little—which was the basis of his *ethics*.

Classification and formal logic

The great contributions of Aristotle were to *logic*, *physics*, *biology*, and the *humanities*; in fact he founded all these subjects

as formal disciplines, and even added *metaphysics* for what would not fit into them. His greatest, and at the same time his most dangerous, contribution was the idea of *classification*, which ran through the whole of his work and was the basis of his *logic*. He introduced or at least codified the way of sorting things based on resemblance and difference that we still use. The questions he asked were: What is the thing like?—genus. And how does it differ from the things that are like it?—differentia. His verbal dodge, the *syllogism*—all men are mortal; Socrates is a man; therefore Socrates is mortal—is still taught as logic today, as if we could ever know the general before knowing the particular.

Aristotle was the first great encyclopædist. He tried to give some account of every aspect of Nature and human life of interest in his time. Moreover, he succeeded, where many encyclopædists after him failed, in doing so in an orderly way. He inherited the order from earlier thinkers. Aristotle took over and effectively canonized the system of four superposed elements, *fire*, *air*, *water*, and *earth*, for the sublunary sphere, and even added a fifth, the quintessence, *ether*, for the upper regions.

The earth, water, and air are peopled with living things each in its proper place with its proper form. Though each individual is subject to birth and death, generation and corruption, the form remains unchanged (p. 631). Aristotle broke definitely with the Ionian school by refusing to consider how the world had been made. The world always was as it is now because that is the reasonable way for it to be. There is no need for any creation. This was somewhat of a difficulty when Aristotelianism was taken as the philosophic basis of the Catholic Church, but it was easily overcome by introducing a sudden creation in the beginning and a sudden destruction at the end and leaving everything in the middle exactly as it was.

Aristotle's physics

The key to the understanding of the world, according to Aristotle, was *physics*. But by physics he did not mean what we mean now—the laws of movement of inanimate matter. Quite the contrary. The *physics* or nature of any being was what it tended to grow into and how it normally behaved. Indeed, Aristotle's thought, because of his medical background and biological interests, interpreted the world as if everything

were alive. He used *physics* in the sense that *nature* is used in the hymn:

> Let dogs delight to bark and bite,
> It is their *nature* to.

The object of scientific inquiry was to find the *nature* of everything. It had to range from explaining why all stones fall, to why some men are slaves. In every case the answer is the same, " It is their nature to." It is, in fact, as comprehensive an answer as to say, " It is the will of God that they should," but it sounds more scientific. As Butler expressed it of a later philosopher, Hudibras:

> He knew what's what, and that's as high
> As metaphysic wit can fly.

In Aristotle's *Physics* and *On the Heavens* he applied this method to what we call the physical universe, where it is most inapplicable. His explanation was hardly more plausible than that of Plato, and lacked both its emotional exaltation and mathematical interest. But because it was part of the great Aristotelian logical universe, it became the main form in which Greek thought on the structure of the universe was transmitted to posterity. This was to prove particularly unfortunate for the progress of physics. Giordano Bruno had to be burnt and Galileo condemned before doctrines which were derived from Aristotle, rather than from the Bible, could be overthrown (pp. 297 f.). The subsequent history of science is largely, in fact, the story of how Aristotle was overthrown in one field after another. Indeed Ramus was not far from the mark when he maintained in his famous thesis of 1536 " that everything Aristotle taught was false."

Final causes

Aristotle built his physical world in the image of an ideal social world in which subordination is the natural state.[2.17.135] In this world everything knew its place and, for the most part, kept to it. Natural motion occurred only when something was out of place and tended to return to it again—as a stone falls through air and water to rejoin its native earth, or as the sparks fly upwards to join the celestial fires. This applies only to such objects as have no natural motion of their own. It is in the nature of a bird to fly in the air, of a fish to swim in the water. That, in fact, is what birds and fishes *are for*. In this can be seen one of his leading ideas, that of *final causes*, in which

organisms and even matter are endowed with a purpose to reach appropriate *ends*. Aristotle admitted other causes such as the *material cause* and the *effective cause*, which provided the material support and made things work, but he considered them inferior to final causes. This doctrine has been a curse to science because it furnishes a glib way of explaining any phenomenon by postulating an appropriate end for it, without having the bother of finding out how the phenomenon works.

Motion and the vacuum

The battle against final causes in science has been a long one, and victory is by no means yet complete. According to Aristotle natural motion is final; all other motion requires a mover, as when a horse draws a chariot, the slaves row a galley, or when the unmoved mover turns the outer sphere of the heavens. What, however, is to be said of violent motion, as when an arrow is shot from a bow? This had long been a difficult question for Greek physics and Zeno had already by a triumph of logic proved that the arrow could not move at all. Aristotle found the solution: the mover was air—" The air is opened up before and closes in behind."

This error led to another which was to prove as great a stumbling-block to later physics. If air is necessary for violent motion and violent motion exists in the sublunary world, the sublunary world must be full of air and a *vacuum* is impossible. The syllogism is complete, but as the minor premiss is wrong the whole argument collapses. Aristotle uses another argument against a vacuum which seems in some contradiction to the first.[2.7.69] Aristotle argues: " as air resists motion, if the air was withdrawn a body would either stay still, because there was nowhere for it to go, or if it moved it would go on moving at the same speed for ever. As this is absurd there can be no vacuum." It is interesting to see that here he states almost word for word Newton's first law of motion, and uses its *a priori* rejection to prove the impossibility of something within a few miles of his head. But in any case a vacuum would not do; to admit it would lead straight to atomism and atheism. The doctrine of " Nature abhors a vacuum " had a practical origin in the experiences of sucking up liquids, which led to the suction pump. In the end it was the limitation of the suction pump that was to lead Torricelli to the production of the vacuum (p. 329).

Biology : the scale of Nature

The inadequacy and wrong-headedness of Aristotle's physics are partly compensated by the extent and quality of his biological observations. The qualification is not the fault of Aristotle, because the valuable contributions he made to the classification and anatomy of animals received comparatively scant attention till our own times, when it was too late for them to be of any help. In biology the idea of final causes is a much more plausible one, as it is an expression of the successful adaptation of organisms to environment—" Oh, grandmother, what big teeth you have!" "The better to eat you with, my dear." The big bad wolf was a perfect Aristotelian and not too bad an ecologist. Nevertheless, even in biology final causes have had a stupefying effect. All that is demanded is a guess at the purpose of an organ or organism.

The guiding idea of Aristotelian biology is that everything in Nature is reaching up to achieve what perfection it can, and that it achieves it in different degrees. This led Aristotle to draw up a scale of Nature with minerals at the bottom, then vegetables, then more and more *perfect* animals, and finally man at the top. Such a scale might be thought to imply evolution, but Aristotle was sure that nothing really changed in the world, and that species must be eternal fixed signposts to perfection or imperfection. Indeed he tended far more to see a beast as an imperfect man, and a fish as an imperfect beast, than the other way round. His immense authority, added to that of Genesis, held off the idea of evolution for more than 2,000 years. The idea of different grades of perfection was useful in another way—it justified the belief that some men are naturally masters, some naturally slaves. If these are so unnatural as not to realize it, wars to enslave them are naturally justified.

Matter and form

The concept of master and slave, of order and subordination, runs through all Aristotle's thought. He expresses it in his adaptation of Plato's ideals, the dual concept of *matter* and *form*. Matter is brute, undifferentiated; form is imposed on it by mind (*nous*). The crudest matter is capable of any form. It has all forms in it *potentially*. The form represents a purpose of perfection, which may not always be reached. In making a statue, for instance, the matter is passive and accommodating

up to a point, but sometimes refractory, as when it breaks the hammer or otherwise refuses to accept the form which the sculptor wishes to impose on it. As a result of this refractoriness of matter, nothing in the sublunary world is *perfect*, each particular thing has *accidental* features, where *matter* and *chance* have thwarted rational *purpose*.

Substance and essence

Aristotle's *forms* are distinguishable from Plato's *ideals* because they are not *universals*, each refers to a particular animal or thing. In Aristotle's terminology the forms are substantial. This word *substance* means to Aristotle something very different from its meaning in modern science. It is a metaphysical character by which a thing is itself and no other. To allow for some measure of change while preserving individuality, underlying each substance there is an *essence*. Thus substantially a man has two legs, but these are not part of his essence, for he may lose one or both of them without ceasing to be a man. The ideas of essence and *potentiality* are biological in character, expressing the lower and upper limits of what an individual of species can reach. In the first case it just manages to exist, in the second it is exhibiting its full powers.

The idea of potentiality opens the way to the conception of evolution of forms from the imperfect to the perfect. Perfection is always conceived following Parmenides and Plato as higher and unchangeable. Living things are sensible and corruptible, higher than them come heavenly bodies, sensible and incorruptible. Higher still is the *rational soul*, insensible and incorruptible, and highest of all is God, the most changeless of all substances and hence the most actual, the most fully realizing its potentiality (Fig. 6, p. 224).

Man and God

Thus the crown of Aristotle's work was its extension to man as a social animal, *zoon politikon*, and beyond him to God. Man contained in himself, following the doctrine of Philolaus, three souls or spirits: the vegetable soul, the animal soul, and the rational soul or *nous*. The last belonged to man alone. The *purpose* of each soul, which was its motive power, was to strive for its own *perfection*; the *vegetative* soul, for *growth*; the *animal* soul, for *movement*; and the *rational* soul, for contemplation. The perfection of the rational soul was to strive for

something even more perfect, which could only be God, the *unmoved mover* of the whole universe, at the same time the centre and the boundary of Aristotle's metaphysics. Aspiration and love can only be upward: " We needs must love the highest when we see it," as a slave for his master, a woman for her husband, and a man for God. Love down the scale is not called for. It was this theocentric conclusion that so endeared Aristotle to the clerical schoolmen of the Middle Ages and helped them to overlook the contradiction between his philosophy and the Bible story of creation.

Taken as a whole, Aristotle's system of philosophy is a magnificently comprehensive rationalization of the experience and attitude of a reasonably well-to-do citizen. Only a mind that combined enormous industry with unshakable complacency could have worked it out. Its genius did not lie in any of its separate parts. Except for a few personal biological investigations, none of it was original; but what was borrowed was taken from the best people. Its peculiar genius lay in its comprehensiveness, its orderliness, and in the unity which was given to the whole system by his logic.

To achieve the comprehension Aristotle had made another innovation of enormous promise for the future. Instead of doing all the work himself or merely discussing it with his colleagues, as was the practice of the Academy, he *organized research*. In the Lyceum, which was probably subsidized by Alexander, Aristotle's young men collected information on nearly everything, from social and natural forms of literature to the constitutions of cities, from animals and plants to stones. What is left of the results today is the most valuable and systematic knowledge of Greek life and thought. Even more valuable is the practice of such investigations. Just as the Academy is the original of the university, the Lyceum is that of the research institute.

The influence of Aristotle

As will be shown in the next section (4.7) the following out of Aristotle's method of research was very soon to undermine or refute most of his own conclusions, including the central one of final causes. Indeed his views on many topics were out of date before he put them forward. His enormous influence on Arabic and medieval thought, however, came in spite of, or perhaps because of, those limitations. The finer

developments of Greek science were either completely lost or, like the work of Archimedes, not appreciated till the Renaissance. They could not be understood except by highly trained and sophisticated readers, not easily to be found in the Dark Ages. Aristotle's works, however, though tough going, did not require, or did not seem to require, anything but common sense to understand them. Like Hitler, Aristotle never told anyone anything they did not already believe. No experiments or apparatus were needed to check his observations, no troublesome mathematics to derive results from them, no mystical intuition to understand any inner significance. Plato, it is true, appealed more to the imagination and had more moral fervour; but Aristotle explained that the world as they knew it was just the world as they knew it. Like M. Jourdain in Molière's *Bourgeois Gentilhomme* they had all been philosophers without realizing it. As long as the world remained the same Aristotle would do, but, as we shall see, the world did not remain the same.*

Taken together, the three great philosophers of the decline of Athens mark a definite arrest of the movement of ideas which had begun with the Ionian philosophers. Because the social order could no longer advance, the idea that Nature itself was changing and developing was repudiated. Philosophy ceased to be progressive and, as part of the same reaction, ceased to be materialist. Idealism in the mystical form of Socrates and Plato, or in the conformist scheme of Aristotle, took its place. Philosophy taught the acceptance of life as it was, and had nothing to offer to those who found it intolerable but that their sufferings were inevitable and were part of the great order of Nature. Such philosophy was well on the way to becoming a religion, but a religion for the benefit of the upper classes alone.

4.7—*ALEXANDER'S EMPIRE*

Hellenistic science

The arrest in general philosophic ideas did not, however, mean the end of practical science; indeed it was to prove a great stimulus to it. It remains true that no great comprehensive attack on the problems of Nature and society was made between the time of Aristotle and that of Bacon and Descartes, for neither the medieval schoolmen nor the Arabs were, or would

even claim to be, their masters. Nevertheless most of the detailed achievements of Greek mathematics, astronomy, mechanics, and physiology come from the next age, that of Alexandrian or Hellenistic science. The reason cannot be an intrinsic one, the later Greeks were at least as clever as the earlier ones. It must be looked for in the social field, in the conditions that discourage general creativity but encourage the working out of limited fields and the development of practical applications.

The great political and economic change that followed within a century of the fall of Athens was the forcible unification of the independent rival city states by new large land empires which, however, drew their culture largely from the same source. How much this change was overdue was shown by the immediate successes of Philip of Macedon and Alexander. The cities were far too weakened by internal class struggles and divided by mutual jealousies to put up effective resistance. The new type of well-drilled and well-equipped mercenary armies could go where they liked. The levies of the old Persian empire, largely untrained peasants led by hereditary nobles, were no match for them, however great their numbers.

In every other way the Greek type of civilization which the Macedonians had simply taken over showed itself superior to those of the older civilizations it overran. In technique, in organizing ability, in knowledge, in art, the Greek way of doing things imposed itself wherever it appeared. Greek merchants and administrators followed the armies, and cities of a Greek type, though often with only a minority of Greeks, were set up, from the first and most famous Alexandria in Egypt to the farthest Alexandria Eschata (Kojand) in Afghanistan. Nor did Greek influence stop there; it spread far and wide beyond the boundaries of the Alexandrian empire. In the Far East its effect was diluted by distance, but the first Indian empire, that of the Buddhist Asoka, was a direct result of Alexander's raid; and something of Greek art, philosophy, and science spread with Buddhism as far as China. At about the same time an analogous, but quite independent movement was taking place there. In 221 B.C. the ruler of the semi-barbarian Chin State created by force of arms the first Chinese Empire of iron age type, and called himself by the name of the legendary first emperor Hwang Ti. Though his dynasty was not to last, the unity of the Empire was never subsequently

lost for long at a time. All through classical times the highly civilized Han Empire bordered those of Persia and India.

The influences of Hellenism on the West were much greater, because there was less indigenous culture to be replaced. The Latin clansmen were rapidly Hellenized, partly influenced by the city culture of the Etruscans, themselves coming from Asia, and partly by that of the Greek colonists of the coastal cities. One city, Rome, after expelling its Etruscan kings, proved more powerful than all the rest, and after a stormy internal political history emerged as the plutocratic republic, which was later, as the Roman Empire, to dominate the whole area.

The Hellenistic city, and the Macedonian empires

The Hellenistic cities differed in many ways from the Greek cities on which they were modelled. First, to the class distinctions that already operated there was added a race or culture distinction between the Greek-speaking official and trading classes, and the natives. These natives in the south and east, though politically suppressed, knew they had a culture of their own far older and by no means inferior to that of the Greeks. Though this division softened with time it lasted to the very end of the classical era, where the old cultures reasserted themselves in a new religious form (p. 188). Secondly, the cities were not independent, but formed part of the shifting empires of the Ptolemies of Egypt, the Antiochids of Syria, and the various dynasties of Asia Minor and Greece. This was a return, though only a partial one, to the state of the old empires with a divine king, a court, and an army, originally Macedonian but later filled with every kind of local levy or mercenary. The citizens might suffer from tyrannical or, even worse, from weak kings, but they could do very little about it. The real decisions were made at court or on the battlefield. They therefore concentrated on making money and enjoying life, while the poor, the natives, and the slaves endured the situation as best they could. The result was the splitting of society to a degree that had never been reached in human history. The citizens had the opportunities to develop a very select and superior culture, but it was doomed to sterility from the start.

The philosophies of acceptance

The spread of Hellenism had indeed taken place at the expense of its internal cultural development. In art, drama,

literature, and politics, the late Greek achievements, particularly those of Athens, were, so to speak, frozen. Good models were copied in the slightly exaggerated and sentimental Hellenistic style; commentary and criticism flourished, but nothing really great and new was produced.

In philosophy there were no real successors to the schools of Democritus, Plato, or Aristotle. Indeed philosophy, which had already parted from science, was from the time of Alexander also parted from political life and became almost exclusively moral. The citizen might now enrich himself, but he no longer shared in ruling the State except by favour of the Court. Philosophy was now concerned with reconciling politically impotent man to the uncertainties of life in an economically insecure and war-ridden world. The *Cynics* and *Sceptics* shrugged their shoulders. The *Stoics* put up a fine show of superior indifference based on the belief in the intrinsic value of virtue, and in a world ruled by unalterable fate which the stars determined. The *Epicureans* urged men to make the best of it, to practise virtue as the surest way to pleasure, and not to worry about the gods who lived far above this world of whirring atoms.[2.2] The philosophy of the ancient world was to peter out in the mysticisms of the Gnostics and the Neoplatonists, and the last echo of its old voice was to be the *Consolation* of Boëthius, in the end of one era but the beginning of another. Between them the philosophers represented what might more properly be called the *religion* of the cultivated upper classes. They were indeed providing the intellectual language in which the cruder, but far more vital, religions of the lower classes were to express themselves as soon as they came to power.

Hellenistic science

The one exception to the general intellectual decay was for a few centuries the development of natural science. There was indeed in certain directions, particularly mathematical, mechanical, and astronomical, a notable new outburst of creative thought. This arose largely on account of the economic and technical consequences of the conquests of Alexander. By throwing open to Greek trade a world far wider than it ever had known, it created a new market which for a time relieved the chronic crisis of the Greek city state: the under-consumption due to the wretched conditions of the poor and the slaves.

The export market for manufactured goods was still a class-restricted one: only goods for wealthy households were produced—chased silver, moulded pottery, blown glass, papyrus, dyed cloth, elaborately patterned textiles—but it was large enough for these goods to be made in quantity. This led to the rise of manufacturing towns employing, for the most part, wage workers kept down by slave competition. At the same time the larger areas under a single government favoured a limited sea trade in the necessities, particularly corn, to feed this non-agricultural population. This led in turn to technical improvements, not only in manufacture but also in agriculture, in which slave gangs were being used on a large scale. Such improvements were the concern of rulers and hence of their scientific advisers. Another and even more pressing need for new techniques lay in the almost permanent state of war between empires, for which ever more complex engines were always in demand. The Macedonian rulers of the Hellenistic States were, unlike the Romans who were to supplant them, brought up in the aura of the prestige of Greek learning; they not only permitted, but encouraged it in all its branches. It was Greek science rather than literature or philosophy that was the main beneficiary.*

The Museum of Alexandria

Indeed the great contribution of Greek science to the science of later times was for the most part derived from the work in the early Hellenistic or the Alexandrian period (330–200 B.C.) and largely at Alexandria itself, the most important Greek city of the new empire of the successors of Alexander—the Ptolemies. Greek science was brought into direct contact with the problems as well as the technique and science of the old Asian cultures, not only those of Egypt and Mesopotamia but also to a certain extent those of India. And now, for the first time in human history, there was a deliberate and conscious attempt to organize and subsidize science. The Museum at Alexandria was the first State-supported research institute, and although its artistic, literary, and even philosophic production was negligible apart from its preservation of ancient texts, it contributed more to science than any single institution had done before and possibly has done since. The scientific work of the Museum, taken together with that of its ex-members and correspondents in the rest of the classical world such as Archimedes, was

far more specialized than any other had ever before been or was to be for another 2,000 years. It reflected the isolation of the Greek citizen to an even greater degree. The scientific world was now large enough to provide a small, appreciative, and understanding *élite* for works of astronomy and mathematics so specialized that even the average educated citizen could not read them, and at which the lower orders looked with awe mixed with suspicion. This enabled the scientists to venture into complex and refined arguments, and by mutual criticism to make enormous and rapid advances. At the same time these advances were very insecure. The whole scientific effort depended on the patronage of an enlightened State. When that went the edifice of learning largely collapsed and, because it had no living roots outside the big cities, was largely forgotten, though it left a few vitally important writings to be brought to light again in the Renaissance.

The main trends of work in the early days of Alexandrian science followed those of Aristotle and his school. The Museum might indeed be considered as the Egyptian branch of the Lyceum, which, as it was better endowed, in a few years came to overshadow the earlier foundation. Strato, *c.* 270 B.C., the most generally competent of the Hellenistic scientists, taught both at Alexandria and Athens and was the last important head of the Lyceum.

The scope of research at both institutions did not, however, embrace the whole of Aristotle's vast programme. His own biological and sociological interests were not developed further except by his immediate successor, Theophrastus, who did for botany what Aristotle had done for zoology and who began a descriptive mineralogy which, though crude, was not substantially improved for 2,000 years. It was especially physics in its *astronomical*, *optical*, and *mechanical* branches that was intensively studied. Instead of Aristotle's preoccupation with *logic* there was a rapid development of *mathematics* along Platonic lines. This was primarily concerned with the inherent beauty of ideal forms and the need to impress them on the merely observable world. Nevertheless it could be, and was, used on a lower plane to provide more exact astronomical descriptions and to reduce mechanics, pneumatics, and hydrostatics to exact sciences.

With ideal conditions for work, improved instruments, and scope for experiments, the cruder intuitions of Plato and

Aristotle were soon left behind. Teleology, the doctrine of natural places and final causes, was abandoned, so was the Aristotelian theory of motion which made a vacuum impossible. Much of the atomic theory of Democritus, which the Athenian philosophers had so sternly expelled, was readmitted. To a great extent the first stage of the destruction of the philosophy which the Middle Ages believed to be that of the Ancients had been accomplished by the beginning of the third century B.C. Boyle would have found himself in complete agreement with the views of Strato. But he was never to learn them. Except in mathematics the advanced thought of Hellenistic times was largely lost. The reason for this has already been touched on. It was the effective isolation—social and ideological—of the scientists of Alexandria, Athens, and Syracuse. They were no longer philosophers. Strato, according to Cicero, "abandoned ethics, which is the most necessary part of philosophy, and devoted himself to the investigation of Nature." They therefore drifted out of the main current of interest, which in those times of crises and decadence turned inward on the inner world of the individual. Their advanced views were not propagated and, except in astronomy, where they were still needed for the more limited tasks of the time, particularly astrology, they were forgotten while the more common-sense and unscientific views of Plato and Aristotle were carefully preserved.

Hellenistic mathematics: Euclid

The mathematical and physical sciences were pursued in the Hellenistic world with two ends in view, the academic and the practical. The academic, which was of course the higher, was centred on mathematics and led to an extension and systematization of one branch—geometry. Numerical calculations were considered definitely inferior and were disguised as geometry when needed. But here solid and admirable results were obtained. Archimedes applied and improved these methods of Eudoxus (p. 130) to determine the value of π to five places—the practical squaring of the circle—and to find the formulæ for the volumes and surfaces of spheres, cylinders, and more complex bodies. This was the effective beginning of the infinitesimal calculus which was to revolutionize physics in the hands of Newton. There was a great study of higher curves for the purpose of solving the classical and useless problems of

FIG. 4.—TECHNIQUES OF EARLY CIVILIZATION

(*a*) Plan of city with elevation of walls from statue of Gudea of Lagash, *c.* 2250 B.C., showing stylus and ruler with different scales.
(*b*) Archaic Greek potter at work with slow wheel.
(*c*) Greek bronze-casters at work.

trisecting an angle and doubling a cube. Of far greater ultimate significance was the elaboration by Apollonius of Perga, *c.* 220 B.C., of the studies of the conic sections—ellipse, parabola, and hyperbola—discovered by Menaechmos in *c.* 350 B.C. His work was so complete that it could be taken up unchanged by Kepler and Newton nearly 2,000 years later for deriving the properties of planetary orbits.

Even more important than their separate achievements was the systematization of mathematics achieved in Hellenistic times. Logical linking of theorems was known before (p. 130)—indeed Aristotle's logic is a copy in words of the geometrical procedure of proof. It was, however, not until Euclid (*c.* 300 B.C.) that a large part of mathematical knowledge was built together in one single edifice of *deduction* from *axioms*. The value of this for mathematics was considerable, as shown by the fact that Euclid is still in one form or another the basis of geometrical teaching. Its value in physical science is more doubtful, emphasizing as it did the superiority of *proof* over *discovery* and of *deductive* logic based on self-evident principles over *inductive* logic based on observations and experiments. The success of geometry held back the development of algebra, as did the very primitive Greek number notation. A partial exception is the work of Diophantus, *c.* A.D. 250, on equations. This work, which comes late, shows internal evidence of the influence of contemporary Babylonian–Chaldean mathematics.*

Hellenistic astronomy: Hipparchus and Ptolemy

The study of astronomy lay midway between the theoretical and practical. According to Plato it was the study of an ideal world in the sky, suited to the dignity of the gods that lived there. Any deviations which could be observed in the real sky were to be ignored or explained away. On the other hand the implied importance of the skies required that the position of the stars, and particularly of the planets, should be accurately known, and known in advance, if there was to be any hope of dodging the predictions of astrology. As a result of these two tendencies, Hellenistic astronomy—the only part of Greek science to come down to us without a break—was largely engaged in trying to make ever more complicated schemes fit the observations without violating the canons of simplicity and beauty. This pursuit encouraged the development both of mathematics and physical observation. It may be said that

astronomy, almost up to our own time, was the grindstone on which all the tools of science were sharpened.

The mathematical basis of astronomy was the spheres of Eudoxus, but for actual working out it was easier to consider planetary motion in the flat and to save the appearances by introducing "wheels within wheels." This was done by the greatest observational astronomer of antiquity, Hipparchus (190–120 B.C.), who invented most of the instruments used for the next 2,000 years and compiled the first star catalogue. His planetary system, though more accurate, was far more complicated than that of Eudoxus and removed its last shred of mechanical plausibility. In the form in which it was presented by Ptolemy (A.D. 90–168) 200 years later it was to be the standard astronomy till the Renaissance. It was accepted because it removed all the difficulties from earth to heaven, where, after all, there is no reason to expect that vulgar mechanics would hold. Further, as it was made to measure—epicycles being added as required—it gave tolerably accurate predictions.

The alternative tradition, that it was the earth that turned, put forward by Ecphantus in the fourth, or perhaps by Hicetas in the fifth century B.C., had never been lost. It was powerfully supported by Heraclides of Pontus (*c.* 370 B.C.), who adopted the system of a revolving earth still in the centre of the universe round which the moon and sun turned, but with the planets turning round the sun and not the earth. This system, which completely describes what is observed, was later to be that of Tycho Brahe (p. 290). The final logical step was taken by Aristarchus of Samos (310–230 B.C.), who dared to put the sun and not the earth in the centre of the universe. This system, however, despite the eminence of its propounder, won scant acceptance largely because it was thought to be impious, philosophically absurd, and violated everyday experience. It remained, however, a persistent heresy transmitted by the Arabs, revived by Copernicus, and justified dynamically by Galileo, Kepler, and Newton (pp. 278 f., 289 f., 334 f.).

Scientific geography

The development of astronomy made a metrical and scientific geography possible for the first time. The problem of constructing a *map* is one of relating the astronomic positions on a sphere, the imaginary parallels of latitude and meridians (midday lines) with the positions of towns, rivers, and coasts, as

reported by travellers and officials. This is equivalent to measuring the *size of the earth*, which was first achieved by Eratosthenes of Cyrene (275–194 B.C.), a director of the Museum. The value he found for the circumference—24,700 miles—is only 250 miles wrong, and was not improved on till the eighteenth century. The conquests of Alexander had greatly enlarged the boundaries of the world known to the Greeks, but there they stopped—there was no economic drive to further exploration east or west, apart from a few lone voyagers like Pytheas of Marseilles (*c.* 330 B.C.), until the time of the Renaissance. The lack of interest in ocean voyages made it unnecessary to develop an accurate navigational astronomy, for coastal voyages could well enough be made with a very elementary knowledge of the stars.

Optics was also a minor appendage of astronomy. The Ancients never achieved a lens—their glass was too full of flaws and crystal was too rare. Their catoptrics—the study of reflections in mirrors—was developed to the extent of arranging illusions and burning mirrors, but had no serious use. On the other hand their dioptrics—the measurement of angle by sights—was used in accurate surveying. In spite of this they never seem to have realized true perspectives, which had to wait till the Renaissance.

Hellenistic mechanics: Archimedes

It was in mechanics that the Hellenistic age furnished its greatest contribution to physical science. The first impetus probably came from the technical side. Greek workmanship, particularly in metals, had reached a high level before Alexander. Transplanted to countries such as Egypt and Syria, with far greater resources at their command, it could be used to effect radical improvements in all machinery, especially those of irrigation, weight shifting, shipbuilding, and military engines. We know that a great crop of apparently new devices appeared around the third century B.C., but their origin is still obscure. They may well have come from the discovery by invaders of traditionally developed machinery of local craftsmen, afterwards written up and further developed by literate Greek technicians. The mutual stimulation of accurate workmanship and precise calculation was to be observed again in the Renaissance. The compound pulley and the windlass may have come from sailing-ships, and gearing from irrigation

works; but the screw seems a somewhat sophisticated invention. Some mathematician may have had a hand in it. On the demands of their royal patrons, philosophers were by then prepared to debase themselves by considering the mathematical design of machinery. Certainly all the legends of Archimedes' war machines must have some foundation, though Plutarch says of him, "He looked upon the work of an engineer and everything that ministers to the needs of life as ignoble and vulgar." [2.39] Archimedes (287–212 B.C.) was one of the greatest figures in Greek mathematics and mechanics, and the last of the really original Greek scientists. He was a relation of Hiero II, the last tyrant of Syracuse, and took a large part in the defence of that city against the Romans. He was killed, while working out a problem, by a Roman soldier who either did not know or did not care what he was doing. Though he was very much in the tradition of *pure* Greek science, we know from the chance discovery of his work on *method* that he actually used mechanical models *to arrive at* mathematical results, though afterwards he discarded them *in the proof*. For the most part his work was not followed up in classical times. It was only fully appreciated in the Renaissance. The first edition of Archimedes' works appeared in 1543, the same year as the *de Revolutionibus* of Copernicus and the *Fabrica* of Vesalius, and had an effect comparable with them (p. 296).

Statics and hydrostatics

In his *elements of mechanics* Archimedes gave a full and quantitative account of the working of the simple machines and laid the foundations of the science of *statics*, a characteristically Greek analysis of the conditions under which forces would exactly balance. He was also the founder of *hydrostatics*, the laws of floating bodies, which was to have two important uses. One was for the determination of the densities of bodies by weighing them in water; this, because it could be used for the testing of precious metals, was taken up at once and never lost. The other, the estimation of the burden of a ship, was well enough known by tradition to shipbuilders and was not calculated till the late seventeenth century (p. 318).

Pneumatics

One radically new branch of mechanics was pneumatics—the study and use of air movements. Here Ctesibius (*c.* 250 B.C.)

and Hero (*c.* A.D. 100) provided many ingenious tricks working by compressed air, mostly for use in temples. Hero even constructed a rudimentary steam-engine working on a jet reaction principle. A more practical development was that of pumps. In this the technical proficiency of the metal-workers produced double-acting force-pumps as good as anything that existed before the present century and cheap enough to be used even in remote Britain. Another pneumatical device was the water-driven wind organ with stops, operated by keys just as our own organs and pianos are.

The mechanical knowledge and attainments of the Hellenistic period were in themselves quite sufficient to have produced the major mechanisms that gave rise to the Industrial Revolution—multiple drive textile machinery and the steam-engine—but they stopped short of this point. It is true they lacked the prime material of that period—cheap cast iron—but they possessed all the means to make it, power-driven bellows were well within their scope. The decisive reason was the lack of motive. The market for large-scale manufactured goods did not exist. The rich could afford hand-made goods, the poor and the slaves could not afford to buy anything they could do without.*

The dawn of scientific chemistry

The mathematical-mechanical character of the science of the Greeks, together with their unwillingness to concern themselves with anything that would dirty their hands, prevented them from making any serious progress in chemistry, though the beginnings of alchemy and the key chemical process of distillation may date back to early Alexandrian times. Whether alchemy and with it scientific chemistry originated in Alexandria is still an open question. The first reliable writings, such as those of Zosymus of Panopolis and Mary the Jewess, come very late in the fourth and fifth centuries A.D. Any theory they had may have been affected by the influence of Chinese alchemy (p. 203). . The technical achievements of Hellenistic chemistry, on which the whole of modern chemistry rests, was due to improvements in glass blowing, needed for the still (ambix) (p. 202), and in the preparation of pure materials.

Natural history

Little need be said about the achievements of the Hellenistic scientists, other than doctors, outside the field of the physical

sciences. The impetus given by Aristotle to a complete study of all aspects of the universe did not last more than a generation. Only a few significant advances were made in the study of animals and plants though a beginning was made on books on practical agriculture.

Hellenistic medicine: Galen

It was in medicine, even more than in astronomy, that the social conditions of Hellenistic and Roman times favoured a continuity of tradition and even a limited advance. The rulers and the wealthy citizens could not do without doctors. Indeed the increasingly unhealthy life they led made them more and more dependent on them. The Museum encouraged much research in anatomy.

Herophilus of Chalcedon (*fl.* 300 B.C.) was a great anatomist and physiologist basing himself on observation and experiment. He was the first to understand the working of nerves and the clinical use of the pulse, and distinguished the functions of the sensory and motor nerves. Erasistratus (280 B.C.) went further and noted the significance of the convolutions of the human brain. Although most of the finest work of the early Alexandrian period has been lost in the original, the essence of it was passed on in the tradition and was incorporated in the vast production of the last of the great classical doctors, Galen (A.D. 130–200). He was born in Pergamum in Asia Minor, but after training there and at Alexandria ended by taking a very lucrative practice in Rome. He in turn became the fount of Arabic and medieval medicine and anatomical knowledge, and acquired a reverence and authority as great in his field as that of Aristotle. The doctors of later times, impressed by his range of knowledge and experimental skill, hesitated to pit their own observations against his. Indeed, the Galenic system was a skilful blend of older philosophic ideas, like the doctrine of the three spirits or souls (p. 132), with acute but often delusive anatomical observations, largely because he was limited to dissecting animals. Galenical physiology, with its ebbing and flowing of spirits and blood in arteries and nerves, with the heart as the origin of heat and the lungs as cooling fans, still indeed lives in popular language. It was as much the basis of human belief about the little world of man—the microcosm—for over 1,000 years as Aristotle's cosmology was about the great world of the heavens. It was not until the

Renaissance had got behind it a comparable mass of observations, and was furnished with a far better mechanical philosophy, that Galen's views could be superseded. How thoroughly that has been achieved is shown by the fact that the first full English translation of Galen has only recently been published.[2.21a]

4.8—*ROME AND THE DECADENCE OF CLASSICAL SCIENCE*

By the middle of the second century B.C. the Hellenistic empires were collapsing in anarchy and under the weight of the more vigorous power of Rome. There was nothing mysterious about its success in achieving power over the Mediterranean world. Whichever native city managed to establish itself as dominant in Italy would have an enormous advantage both over the Greek or Phœnician city states and over the Asiatic Hellenistic empires, all of which had suffered from centuries of wasteful exploitation which had left them politically and economically weakened. Italy was still, in the third century B.C., a farming country with a good climate and plenty of timber, just in the first flush of expansion, with a growing, healthy population. Its slow early growth had left Rome far nearer the clan organization of society than the cities of the older civilizations. The Roman republic could count in its wars on popular support, which the others could never do. Arming themselves repeatedly with the techniques of their more advanced enemies, the Romans could be beaten in battle but they could not be conquered. Rome's only serious rival was the commercial republic of Carthage, which could match it in wealth but not in manpower.

Internally Rome had experienced essentially the same class struggle that had racked the Greek cities, but in an even more naked form, expressed in the rivalry of patricians and plebeians for control of the State. In the first century B.C. this culminated in bitter civil wars which paved the way to military dictatorship and later to empire. Indeed, the acquisition of the Empire was one means by which the rich could buy off the poor with a small portion of the loot of provinces. Another was the policy of extending Roman citizenship first to Italian and then to other provincials, thus turning what was originally a city state into a territorial State dominated by slave-owners and wealthy merchants. Piece by piece the States of the eastern and

western Mediterranean fell into Roman hands and at the same time they opened up the barbarous hinterlands of Gaul, Britain, western Germany, and Austria. The result was the formation of a great new empire, occupying the whole Mediterranean area, but sharing the Hellenistic kingdoms with a newly liberated Persia.

The cement of the Empire was the army by which it had been won, and by which, with decreasing success after the time of Augustus, it was defended against barbarians. The emperor, as commander-in-chief, usually managed to impose and collect enough taxes to keep the soldiers from mutinying and choosing another emperor. The Empire was effectively a loose federation of cities managing themselves and profiting for their mutual trade from the internal Pax Romana. The best land of the countryside was farmed by slave gangs of the villas of the wealthy. The poorer areas—the *pagi* or rustic communes—were left to the natives—the *pagans*—largely following their own tribal customs (later to become the peasants of the Middle Ages and to give their name to the country or *pays*) or to newly settled *coloni* and freed slaves who gradually became serfs—*villani*, villeins, or villains.

The spread of the Roman Empire had a very different effect on culture from that of Alexander's conquests. By the time the Romans came on the scene the impetus of Greek civilization had already passed. In science and art it was already decadent. In another sense the Romans came on Greek civilization too late: their own economic system, based on wealthy patricians and their clients, was far too set to make effective use of science. Besides, the Roman upper class, and while the Empire was being built they were the only Romans that counted, though they adopted the trappings of Greek civilization, despised it. Neither they nor the new provincials of the West added anything significant to it. The best that they could do was to pick up some of the general ideas of Greek philosophy and use them to support their own form of class rule. The elder Cato, a country diehard of the second century B.C., hated Greek science and made no bones of it. According to him Greek doctors came over to poison the Romans, and philosophers to debauch them. Cicero, a rising lawyer a century later, took a much more enlightened view. He found much to praise in the philosophy of Plato and Aristotle, which justified the rule of the best people, but suspected that the Epicureanism

which his countryman, Lucretius, was introducing would shake the people's faith in the gods and hence in established order. However, the philosophy most in vogue, especially in the days of the Empire, was Stoicism. Though Stoicism had started as a philosophy of resistance, rather like early Existentialism, its emphasis on virtue for its own sake gave the Roman administrators, and even an occasional emperor like Marcus Aurelius, a sense of sacrificing themselves, without thought of reward, for the public good. Seneca, the most distinguished of the Roman Stoics and the tutor of the artistic emperor, Nero, saw nothing odd in accumulating a large fortune—no doubt as a sacred trust.

It is customary to blame the practical spirit of the Romans for the sharp decay of science that set in about the time of the first Roman emperors. It is much more probable that the causes were deeper: they lay in the general crisis of classical society, which flowed from the accumulation of power in the hands of a few rich men (whether they were at Alexandria or Rome did not much matter), and also in the general brutalization of a population of slaves and of what we may call, from more recent analogies, " poor whites." Their impoverishment lowered the demand for commodities, which depressed still further the condition of merchants and craftsmen. This was an atmosphere in which there was no incentive for science, and in which the science that still existed carried on from inertia and very soon lost its essential quality of inquiring into Nature and doing new things.

Public works and trade

The application of existing knowledge could, however, for several centuries be made more extensively and on a larger scale than ever before. Not only could gigantic public works such as roads, harbours, aqueducts, baths, and theatres be constructed, but unrestricted trade could flourish and products from all parts of the Empire could be freely interchanged. This led, for commodities like pottery, to what was practically factory production of standardized articles. However, with abundant slave labour and a market still restricted to the well-to-do classes, the master manufacturers had no incentive to take the next step of introducing machinery, and the conditions for developing an industrial revolution never arose.

Architecture

The two characteristic contributions of Roman technology were to architecture and agriculture. The building of aqueducts, amphitheatres, and large basilicas called for the development of the arch and the arched vault—made possible by the lavish use of burnt brick and of a concrete made from lime and volcanic ash. In spite of its massive impressiveness, Roman architecture shows far less sense of the exploitation of the possibilities of arch and vault than does the medieval Gothic. It was only in the very last stages, and that in Constantinople, that the really ingenious construction of the light pendentive supported dome was evolved from Persian models.

Agriculture

Agriculture could hardly become a science until far more was known of biology than could possibly be known to the Ancients. Indeed it is hardly a science yet. The agricultural writings of the Romans, of which the best known are the *Georgics* of the poet Virgil, are necessarily limited to recordings of peasant practice together with some grim reminders of estate management based on slave labour. They are none the less interesting in showing how, particularly in fruit and vegetable gardening, most of the techniques of today were well known and practised. On the other hand, lack of suitable horse harness and ploughs set a limit to the kind of land that could be cultivated.

Administration and law

The great positive contribution of the Romans to civilization that is found in every history book is their creation of a system of law. Now Roman law is anything but a scientific attempt at securing fair dealing between man and man; it is frankly concerned with preserving the property of those fortunate enough to have acquired it. It contains, as Vico first saw, the relics of three superimposed layers of cultural history. First, there is the old tribal custom, evolving from its matriarchal to a most severe patriarchal stage under the influence of the monopolization of movable property in cattle (*pecunia*). This is the celebrated Roman *family* system in which the paterfamilias despotically rules his wife, children, and *famuli* or slaves. Next comes the imprint of city and merchant law, the result of the long economic and political struggles of the Republic, with its emphasis on cash and recovery of debt. Last is the effect of the

Imperial administration with the recognition of the *prerogative* of the prince. In its final codified form, at the very end of the Empire under Justinian in the sixth century, it shows the influence of the severe Stoic philosophy which, like Confucianism in China, had become the second nature of the Roman officials. There is much social history to be learned from Roman law, but it contributed to science only the concept of a universal *law of nature*. Inapplicable essentially to the totally different economy of the feudal period, it was revived, with all the aura of the greatness of the Empire, in the Renaissance as the basic code of capitalism (p. 714).

Decline and fall

In the latter days of the Empire, from the time of Hadrian (A.D. 117–138), the whole economy began to break down. The army, which had been a great source of wealth in slaves and loot, became an increasing but necessary burden, for now new lands were no longer being conquered and the Empire was finding its own defence increasingly difficult.* Attempts at reform only made things worse in the long run. Money economy was undermined by inflation and gave way to barter, based on exchange of goods largely locally produced and consumed. The *villas*, in which the rich took refuge to escape taxation, became centres of local production and gradually replaced the old cities as economic centres, and trade became more and more limited to luxuries. These were only the last symptoms of a disease that was inherent in the class society of the ancient world. There was no way of getting rid of exploitation short of a complete breakdown.

Economic and intellectual decay

Classical civilization was already intrinsically doomed by the third century B.C., if not earlier. The tragedy for science was that it took so long to die, because in that period most of what had been gained was lost. Knowledge that is not being used for the winning of further knowledge does not even remain—it decays and disappears. At first the volumes moulder on the shelves because very few need or want to read them; soon no one can understand them, they decay unread, and in the end, as was the legendary fate of the Great Library of Alexandria, the remainder are burnt to heat the public-bath water or disappear in a hundred obscure ways.

Mysticism and organized religion

Thought did not stop with the fading away of natural science; it merely turned once more towards mysticism and religion. Though the emotional drive to mysticism is the desire to escape from this wicked world, it had an elaborate philosophic intellectual foundation, deriving from Plato at the time of the decay of the democratic city state. The subsequent schools, particularly the Stoics and the Neoplatonists, developed the mystical side of Plato's idealism and left out the mathematical, except in the form of a cabbalistic numerology abounding in magic squares and mystic numbers. From the first century onwards, philosophic mysticism fused with that of the salvation religions, of which Christianity was the most successful. Their common intellectual feature was a reliance on *inspiration* and *revelation* as a *higher* source of *truth* than the *senses* or even than *reason*: as Tertullian expressed it, "I believe *because* it is absurd."

The rise of these religions was itself a symptom of the hopelessness of the slave, and even of the citizen, in the face of a system that ground him down and from which it seemed impossible to escape (p. 183). He could take his choice of indulging in almost revolutionary denunciations of the system, such as are found in the Apocalypse, and stirring up resistance to official worship; or of retiring to the desert to avoid contamination with the evil of the world. To the religious it was not only idolatry but all that went with the hated, upper-class State that was abominable; the luxury, the art, the philosophy, the science were all signposts on the way to hell. Augustine and Ambrose, turning from wicked learning to holy nonsense, were just as much part of the movement as the monk-led mob who stoned Hypatia, one of the last of the Greek mathematicians. Only when the old classical world was utterly destroyed, as in the West, or tamed, as in the East, could the Church allow, and then very gradually and reluctantly, a limited secular science. How this happened will be told in the next chapter, which will trace the rise of the new civilizations which stemmed from the decay of the classical world. Here also will be found an account of Christianity, which though it arose out of classical civilization was a product of popular opposition to all that it stood for and properly belongs to the next stage of society. Despite its opposition to classical culture it would be absurd to blame Christianity for its decline and fall. It was a symptom rather than a cause.

The mysticism, the absurdity, the confusion and decay of late classical times were the products of the social and economic collapse of the plutocratic slave State. In Aristotle's sense it was far gone in corruption; in the Chinese phrase, it had exhausted the mandate of Heaven. Although the rule of nominally Roman emperors in Constantinople was to last another thousand years, that empire belonged to a new age.

The barbarians

The final phases of the break-up of classical civilization took a different form in the older civilized and Hellenized eastern parts of the Empire than in the relatively recently conquered West, where city life was a foreign importation and the countryside was still largely pagan. The East absorbed its barbarians. City life never ceased and passed with hardly a break into the rule of Islamic Caliphs, and that of the (far more Greek than Roman) Byzantine emperors. The new structure of the States was not the same as the old, but trade, culture, and learning were preserved and for a while brilliantly revived.

In the West there was something like a general economic collapse of which the barbarian invaders took advantage. The barbarians were not themselves responsible for that economic breakdown. Far from invading the Empire, in the first place they were introduced into it as mercenaries, slaves, or serfs, largely to make up for the shortage of labour which the killing exploitation of the Roman landlords and tax-gatherers had already produced. Further, the Roman technique had not developed far in the practical field of food production in the heavily forested lands of the North and West. There seems to be no doubt that the barbarians themselves had better agricultural techniques than the Romans they displaced. At least they were able to cultivate the fertile and heavy soils of western Europe which the Romans neglected. In Britain, for example, the Roman estates covered only a fraction of the land occupied and effectively tilled by the heathen Saxons (pp. 208f).*

Loss of organization and technique

What was lost in the barbarian invasions of western Europe was everything of culture that depended on large-scale material organization. Bridges, roads, aqueducts, irrigation canals, all fell into decay and largely disappeared. So did the distribution of standardized goods, such as pottery, from a few central

factories. The only fine techniques to survive and flourish were those producing portable objects of fine metal-work for ornaments and weapons. With the disappearance of a literate class of wealthy people and their dependants in the cities there was little left of the tradition of philosophy, and hardly anything of science. Late classical scholars took refuge in the Church, like Gregory of Tours or Paulinus of Nola, or became officials of barbarian kings like Boëthius, or retired to their estates like Ausonius (*c.* A.D. 310–*c.* 395). Nevertheless enough was left in Europe of the classical culture to enable it to be reborn, purged of most of its limitations of the days of the Empire. In Venice, Salerno, and far-away Ireland were sources from which the fresh and original medieval culture was to flow, and to meet again in the twelfth century the main stream that had flowed through the Islamic East.[3.1a; 3.30–32]

4.9—*THE LEGACY OF THE CLASSICAL WORLD*

This book is concerned with the influence of science on history, and in particular with that of the natural science of the classical world on the life of the times and of succeeding ages. This chapter should serve to bring out something of what science meant and effected in the life of the Greek city. We are apt to be so dazzled by the intellectual and artistic brilliance of the Greeks that it is difficult to realize that their knowledge and skill affected far more the appearances than the practical and material realities of life. The beauties of Greek cities, temples, statues, and vases, the refinement of their logic, mathematics, and philosophy, blind us to the fact that the way of life for most people in civilized countries was, at the fall of the Roman Empire, much what it had been 2,000 years before when the old bronze age civilization collapsed. Agriculture, food, clothes, houses, were not notably improved. Except for a slight improvement in irrigation and road-making, and for new styles in monumental architecture and town planning, the science of the Greeks found little application. This is not surprising; for in the first place science was not developed by well-off citizens for that purpose, which they despised, and in the second, even with the best will in the world, the science they had acquired was far too limited and qualitative to be of much practical use. Greek mathematics, elegant and complete as it was, could be applied to few practical purposes for the lack of

either experimental physics or accurate mechanics. The chief fruit of the magnificent Greek astronomy was, apart from astrological predictions, a good calendar and some indifferent maps. The great nursery of applied astronomy, the art of the navigator, hardly existed for lack of ships or incentives to sail the trackless ocean.

The other natural sciences were hardly more than discursive catalogues—such as Pliny's great *Natural History* 8.52—of the common observations of smiths, cooks, farmers, fishermen, and doctors. Where science intervened it was to impose naïve or mystical theories, based on elements or humours, which confused and distorted the understanding of Nature. The consequences of the social sciences of the Greeks were more direct, though just because they were relative to the conditions of a city state they became inapplicable when these changed (p. 714). The techniques, in contrast to the sciences, lasted far better and lost less. Indeed, except where they depended on scale, like the making of roads and aqueducts, they were transmitted unchanged in essentials, though, at least in the West, they were debased and simplified in expression.

The full possibilities of classical culture could not be realized in the framework of the civilization which gave it birth. They were blocked at every turn by the social and economic limitations inherent, as we have seen, in a slave-owning plutocracy. The real contribution of Greek science was to be in the future, though it could be made only in so far as the germinal elements of the classical culture could be preserved and transmitted. Fortunately, though classical civilization had not the power to save itself, it had enough prestige to ensure that at least some of its achievements could never be forgotten and could later become the basis for new growth.

What had happened in the period of Hellenic and Roman power was a great spread of civilization all the way from the Atlantic to the Hindu Kush. The prestige which the extent of the power and the culture of these great empires generated far outlasted their political sway. It served, even after its original impulse was spent, to spread over a far wider area the ideas, the methods, the styles, and the techniques of Hellenism. In the East, Central Asia, China, and India all felt its influence blending with those of old native cultures; in the West the prestige of the lost learning served to tame the barbarians of Europe.

Indeed, perhaps the most important salvage of the Classical

Age was the very idea of Natural Science. The belief persisted, as legends attest, that the Ancients through deep study had acquired a knowledge of Nature that enabled them to control it. Alexander, instructed by Aristotle, had a submarine and could fly through the air in an eagle-powered chariot. Of the actual elements of classical culture, science, particularly astronomy and mathematics, proved in fact the most lasting. Because they were needed to chart the planets, if only for astrological predictions, they had to be handed on and practised. Much of the other sciences was preserved in books, to be rediscovered at intervals by the Arabs and the Renaissance humanists. We shall never know how much was irretrievably lost, but certainly enough came through to guide and stir the thought and practice of later ages. So much, indeed, was rediscovered and imitated in the last 500 years that we have effectively incorporated the classical world in our own civilization, and nowhere more consciously or fruitfully than in technology and science.

TABLE 1.—*The Development of Techniques and the Origins of Science*

(Chapters 2, 3, and 4)

This table shows the main technical developments from the period of the first human societies to the beginning of the classical period about 600 B.C. The dates are given only to indicate the beginning of the characteristic cultures of palæolithic, neolithic, bronze, and iron, at their main centres of origin. Elsewhere they appear much later. In eacb period the arrangement is not chronological but merely a list of the most significant features of the stage of culture.

TABLE 2.—*Techniques and Science in Classical Times*

(Chapter 4)

This table covers the 1,100 years of the development of rational science, predominantly Hellenic, to bring out its relation to contemporary history and technique. The period is divided into centuries and as far as room allows individual contributions are attributed to the century in whicb they occur. No significance can be given to finer time intervals. The time-scale is uniform and tbe crowding of names in the Athenian and Hellenistic period brings out the great scientific activity in those periods compared with the comparative sterility of the Roman period.

MAP 1.—*The Beginnings of Civilization*

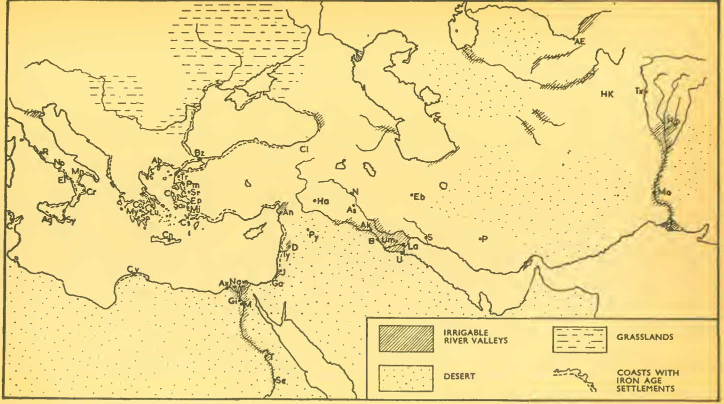
This map shows the major areas, with the exception of the Chinese plains, in which we have evidence of the origin of agriculture and the building of cities. Most of the area, apart from high mountains and deserts, consisted originally of open grass-covered plains where pastoral culture could take form; the flood plains and deltas of important rivers, which are suggested as the first localities for cities; and the coastal areas opened up in the Iron Age. The localities of the principal cities of the Bronze and Iron Ages are also indicated.

Table I

	Basic Food Production and Transport	Tools and Materials	Equipment and Processes	Social Organization	Intellectual and Cultural Achievements
The Palaeolithic Age (Chapter 2)	Food gathering and hunting Organized big-game hunting Canoes Fishing, trapping Grain and root collecting	Stone implements Hand tools and weapons Hafted tools: hammer, axe, and spear Bow and sling Bow drill	Fire Cookery Roasting Prepared skins Clothes, bags, and buckets Thongs and twine Nets and ropes Baskets	Small social groups Totemic clans Hunting rites Burial rites Magicians	Language Animal and plant lore Ritual dancing, songs, and music Myths Naturalistic painting and sculpture Medicine and surgery
The Neolithic Age (Chapter 3.1)	Agriculture Shifting hoe culture Domestic animals for food, wool, pack, and draft use Food storage Plough Permanent fields	Ground stone tools: axes, hoes Hand mills Rough carpentry Ornaments of native gold and copper	Pottery Spinning Weaving Reed and clay huts, wooden houses Baking and brewing	Villages Fertility rites Rain makers and corn kings Emergence of social differences Ritual exchanges	Calendar for agricultural use Geometric design Symbolism Creation myths
The Bronze Age (Chapter 3.2–3.8)	Irrigation Water-lifting devices Canals and dams Sail boats Wheeled carts Roads Horse chariots	Metal Mining and smelting Copper and bronze casting Bronze tools, saws, chisels Weapons and armour Riveting, soldering, metal vessels	Brick and stone building Many-storied houses Joined furniture Chairs, beds, tables Beer and wine Glazed pottery	Cities Class societies Gods and temples Priest kings Craftsmen, traders, law, property, and debt City states and war Empires and slavery Barbarian irruptions	Ideographic signs Accounts Numbers Writing Weights and measures Arithmetic and geometry Solar calendar Astronomy Professional medicine
The Early Iron Age (Chapter 4.1–4.3)	Increased forest clearance and ploughing Waterwheels and pumps Gearing and pulleys Improved sea-going ships	Iron Improved and cheaper tools and weapons Catapults and other war machines	Glass Improved preparation of drugs and dyes	Trading cities Politics Republican government Rise of plutocracy Social struggles Intensified warfare	Alphabet Literature Coined money Philosophy Birth of rational science
	Biology	Physics and Mechanics	Chemistry	Social Sciences	Astronomy, Mathematics, and Medicine

Table 2

Date	Chapter	Technical Developments	Political and Social Events	Philosophy and Science	
B.C.			Age of tyrants	Influence of Babylonian and Egyptian learning	
—600		Acquisition of Eastern techniques		*Thales* and the Nature Philosophers Materialist theory of the universe	
	(Chap. 4.5)		Persian conquest of Ionia Greece liberated from Persians	*Heraclitus* philosophy of change *Anaxagoras* heavens not divine	*Pythagoras* number and form, physical law
500		Mining and metal-working Shipbuilding Architecture and sculpture	Pericles in Athens Peloponnesian War Athenian democracy	*Empedocles* four elements *Hippocrates* rational medicine	*Philolaus* spherical earth *Parmenides* change illusory *Democritus* atomic theory
—400	(Ch. 4.6)	City building on grid plan	Defeat and reaction in Athens Triumph of Macedon Alexander's conquests	*Socrates* the dialectic method *Plato* Idealism *Eudoxus* heavenly spheres	*Aristotle* Reason and Logic, descriptive biology
—300	(Chap. 4.7)	Geographical information on Persia and India Great development of water-works and military engineering	Hellenistic influence in Egypt, Persia, India, and Central Asia Carthaginian Wars	Museum of Alexandria *Euclid* ordered geometry *Strato* experimental physics *Erasistratus* human anatomy *Apollonius* conic sections *Ctesibius* mechanics and pneumatics	*Theophrastus* mineralogy *Epicurus* atomic philosophy *Aristarchus* rotating earth *Archimedes* mechanics, hydrostatics *Eratosthenes* map and size of earth
200		Mechanical toys Great spread of slavery	Roman control of Greek world		*Hipparchus* observational astronomy, precession of equinoxes
—100			Roman civil wars Conquest of Gaul *Cæsar* reforms calendar	*Cicero* Greek philosophy for the Romans	*Lucretius* atomic materialism, science without religion
0		Spread of Roman Architecture based on circular arch and vault	*Augustus* first Roman Emperor Jewish revolt Spread of Christianity	*Pliny* encyclopædia *Dioscorides* descriptive botany	*Strabo* geography *Hero* mechanics, steam engine *Vitruvius* architecture
A.D. 100	(Chap. 4.8)	Water-mills	*Marcus Aurelius* the philosopher emperor	*Galen* codified medicine and physiology	*Ptlemy* "Almagest," descriptive astronomy
200		Decline of city economy and trade	Crises and barbarian invasions *Diocletian* attempts to stabilize Empire *Constantine* Christianity official	*Zosimus* rise of alchemy, distillation	*Pappos* calculation of areas and volumes *Diophantus* numerical equations
300			Condemnation of Arianism		
400			Breakdown of Western Empire Rome sacked by Goths *Augustine* "City of God" Nestorian heresy		*Hypatia* murdered *Proclus* last Greek mathematician
—500					



MAP 1.—(SEE P. 171)

Ab—Abdera **Ag**—Agrigentum **Ak**—Akkad **Ax**—Alexandria **AE**—Alexandria Eschata **An**—Antioch **As**—Assur **A**—Athens **B**—Babylon **Bz**—Byzantium **C**—Carthage **Cl**—Chalybes **Ch**—Chios **Cn**—Cnossus **Co**—Corinth **Cs**—Cos **Cr**—Croton **Cy**—Cyrene **D**—Damascus **Eb**—Ecbatana **El**—Elea **Ep**—Ephesus **Ga**—Gaza **Gi**—Giza **Hp**—Harappa **Ha**—Harran **HK**—Hindu Kush **J**—Jerusalem **La**—Lagash **Lu**—Laurion **M**—Memphis **Mn**—Metaponton **Mi**—Miletus **Mo**—Mohenjo-daru **My**—Mycenæ **Np**—Naples **Na**—Naucratis **N**—Nineva **Py**—Palmyra **Pm**—Pergamum **P**—Persepoles **R**—Rome **Sa**—Samos **Sr**—Sardes **Sp**—Sparta **S**—Susa **Sy**—Syracuse **Se**—Syene **T**—Thebe **Tr**—Troy **Tx**—Taxila **Ty**—Tyre **Um**—Umma **U**—Ur

Part III
SCIENCE IN THE AGE OF FAITH

INTRODUCTION

The period covered by this section is a vast one, ranging from the fading out of classical Græco-Roman culture in the fifth century to the dawn of a new culture based on a new economic system and a new experimental science in the Renaissance. Nevertheless, for the objective of this book, the historical process over these ten centuries has a dynamic unity. Throughout the whole period we are seeing the decay, transmission, recovery, and the beginnings of the inner transformation of the body of techniques and beliefs that stem largely from the Hellenistic world. This holds not only for Europe but also for Asia, where, except for China, where a still older tradition remained dominant, technique and science had drawn deeply from the same source. The emergence of modern science is understandable only in terms of the Hellenistic world-picture epitomized in Plato and Aristotle. Throughout most of the period, indeed until well into the fifteenth century, the main intellectual task was one of recovering that picture and adapting it to the new, essentially feudal, economy that nearly everywhere accompanied the breakdown of that of slave-owning plutocracy. It was also necessary to adapt it to the cramping intellectual requirements of the dogmatic religion of Christianity, which had survived the breakdown of the old world and that of Islam, itself largely a product of that breakdown.

That this was possible at all, and that no radically new world-picture was needed, is an indication that the economy of feudalism, technically and economically more fragmented and primitive than that which it replaced, did not have great need for radically new intellectual forms and accordingly could not develop them. What it could and did do was to introduce new

productive techniques which, though on a smaller scale, were far more widespread and closer to the people than were those of classical times. It was, as we shall show in Part V, this feature of later medieval life and the economic changes which accompanied it that gave rise to the radical transformation of the sixteenth century which at the same time created *modern science* and *capitalism*.

To explain the birth of modern science we need to know its antecedents, something of the long and very obscure period of preparation which led up to it, something of what it owes to the cultures of the classical and pre-classical civilizations as well as to those of Islam, Persia, India, and China. Most of all we need to know how it came about at all. What led to the appearance of the new science in the sixteenth century in Italy? What made it flower so abundantly in the England, France, and Holland of the seventeenth? Why had the same decisive steps not been taken in other cultures, such as those of India and China, which seemed ready for them at different periods of their history? These questions and some attempt to answer them form the central theme of this section. In it will be found an assessment of the factors that contributed to the rise of modern science. The most important of these are shown to be the economic tendencies, which in increasing measure throughout the later Middle Ages put a premium on technical advance, particularly in the direction of labour-saving. These are the same tendencies that mark the transformation of the economic structure of *feudalism* into that of *capitalism*. Indeed the track in time and place of the growth of capitalism in Europe is the same as that taken by the development of science. It will be shown how, in the early stages, science followed the development of nascent capitalism and how gradually it came to influence that development itself. The general character of science over the whole period was dictated by the existing feudal conditions which limited it rather than by anticipation of a different social state which was still to come.

The periods covered in Part III include that of the origins, the growth, the flowering and the decay of the feudal economy in northern Europe and the Mediterranean lands, together with the parallel but distinct developments in Asia, whose contribution to world culture was greatest of all in this time. They fall naturally into two very unequal parts. First, in Chapter 5, comes the transitional period of some 700 years, A.D. 450–1150,

characterized in Europe by the salvage of a residue of classical techniques and science, and by their continued development in Syria, Egypt, Persia, India, and China, all under the impulse, direct or indirect, of Hellenistic culture. The results of all these were fused together towards the end of the period in *Islamic* culture, which, in its short but brilliant flowering, acted at once as the transmitter and stimulator of a new advance in science.

The second period—that covered in Chapter 6, A.D. 1150–1440—is a distinct one only to Europe. It begins in the field of science with the impact on a vigorous feudal society of the Islamic version of Hellenistic science, leading to the brilliant but unsustained movement of medieval scholasticism. It is also marked by a slow but accelerating movement of advance of techniques and scientific interests under conditions of an increasingly unstable *feudalism*. This advance in itself and in its economic consequences prepared the way for the next social form of *capitalism* in which *modern* science came into being, as will be told in Part IV.

Chapter 5

SCIENCE IN THE TRANSITION TO FEUDALISM

5.1—*THE DEVELOPMENTS OF CIVILIZATION AFTER THE FALL OF THE ROMAN EMPIRE*

In our traditional education attention has been so fixed on the history of the Roman Empire, and particularly its western section, that we are apt to think that a general destruction of civilization occurred from the third to the ninth centuries. In fact all that happened was that in the most lately and artificially civilized parts of the ancient world, Britain, France, the Rhineland, Spain, and Italy, a system of government by a class of wealthy slave-owning patricians and provincials collapsed and was gradually replaced by a much more widely based, though incoherent, feudal order. The barbarian invasions that accompanied this change were its result and not its cause.

Meanwhile, over the rest of the Roman Empire, great cities such as Alexandria, Antioch, and Constantinople, survived undamaged and orderly government, though increasingly restrictive, was maintained. Well beyond the bounds of the Roman Empire, over the whole territory which since Alexander's raid had fallen under Hellenistic influence, including Persia, India, and Central Asia, civilization continued to flourish and develop, but without the rigid economic, technical, artistic, and scientific limitations of late classical culture. The great periods of the Sassanian Empire in Persia (A.D. 226–637), of the Guptas (A.D. 320–480) and Chalukyas (A.D. 550–750) in India, and of the less known kingdoms of the Chorasmians in Central Asia (A.D. 400–600), all overlap the interval between the fifth and the ninth centuries that we call the Dark Ages, as if, because little is known of what happened in a very partially civilized western Europe, a great darkness covered the whole earth. Further still, China under the Wei (A.D. 386–549) and T'ang (A.D. 618–906) dynasties was enjoying a period of unexcelled economic and cultural achievement.[3.4]

In their economic and political structure all these States had not departed as far from the pattern of the early bronze age civilizations, which had existed in their territories, as had the cultures of Hellenized and Romanized countries. They had never undergone the intense economic and political struggles arising out of a money economy and slavery, which had first made and then destroyed classical civilization. In other respects their cultures were very different from each other. Persia was still dominated by an old tribal nobility and the simple religion of Zoroaster was being restored to vigour by a reforming dynasty. India had already, by the sixth century, developed the complex religious and caste system which Buddhism had been powerless to check, while China was well set along the path charted by Confucius with the dominance of a highly educated country gentry, though its culture still preserved many features of primitive clan society [2.22a] expressed in the cult of ancestor worship.*

Though each culture followed its own pattern, they were at this period far more in contact with each other than before, particularly through the medium of trade. As a result of a wide market, though one limited to luxuries, manufacturing techniques improved, especially in weaving, pottery, and metal-work. The draw loom, irrigation machinery, and probably many of the key inventions in mechanics and navigation that were to transform Europe in the Middle Ages, arose in the East at that time. Art certainly flourished mightily, as the treasured objects of this period in our museums show. Although Hellenistic art was enthusiastically taken over as far as India and beyond, its cold ideal forms were rapidly transformed and given a new and sensuous life.

Of science we know little outside India and China, but we can infer from their rapid later flowering under the protection, but not necessarily under the impetus, of Islam that it was as much cultivated in Persia and Central Asia. Greek influence is visible particularly in mathematics, astronomy, and medicine, but transplanted to a new medium it could grow in a way that it could no longer do in its own country. All these developments were later to contribute to a common cultural advance, but they are not by themselves as important as the basic economic changes which accompanied them.

The decline and fall of the Roman Empire marked a definitive era in the history of the whole of humanity. In its prime it had

been the largest State in the world. Its military and civil organization and its trade had reached the limits of size of any human community for many centuries to come. None of the States which took its place over its old territories ever managed to maintain such an organization for such a time over so large an area. Outside it the only comparable empire was that of China, and the character of Chinese State organization was very different from the classical one. As the Roman, plutocratic, slave economy disintegrated, for reasons already discussed, it left behind it almost everywhere the seeds of a new decentralized economic and political system.

There are marked resemblances but even greater differences between the immediate consequences of the Roman collapse and that of the old bronze age civilization 2,000 years before (p. 98). In both cases life took up again from a lower technical level, but in the later case the relative economic fall was even greater, at least in Europe. On the other hand, as we shall see, much more was salvaged of knowledge and culture. What disappeared, as in the earlier case, was everything dependent on large-scale operation, communications, long-range trade, waterworks. What took the place of the Roman Empire was, however, something quite different from the swarm of trading and ultimately democratic city states that marked the beginning of the Iron Age.

The transition to feudalism

Despite the continued existence of cities in the Eastern Empire the economy of the new order was everywhere essentially country based, the unit being the estate, villa, or manor worked by serfs, rather than chattel slaves, who were permanently attached to the land with rights to compensation for their heavy duties. The estates were owned either by the descendants of the old city plutocracy, as happened mostly in the Eastern Empire, or by barbarian clan chiefs in territories occupied by Germans or Arabs. The economy of the countryside was essentially feudal both in the lands of the East, where the owners at first lived largely in the towns, and in the West with its poorer communications where they lived on their estates.

In most cases the peasants, *coloni*, serfs, *rayats*, remained in possession of the land and tools, but were forced to yield part of the produce or labour to their lords in the form of rent, taxes, or feudal service. The standards of land use reverted in

the West to a subsistence economy, but one on a higher technical level than that of the Iron Age. In the East a larger surplus always remained for trade. The transformation to feudalism naturally did not occur all at once, it took several hundred years, nor did it proceed at the same speed in different places. Before feudalism reached its full extent it had already begun to decay at the centre. Nor was it limited to the areas of the old Greek or Roman Empires. As the predominant economic mode it spread as new land was opened to cultivation in Europe and Asia.

5.2—*THE AGE OF FAITHS*

The conditions of feudal production reduced the demand for useful science to a minimum. It was not to increase again till trade and navigation created new needs in the later Middle Ages. Intellectual effort was to go in other directions and largely in the service of a radically new feature of civilization—*organized religious faiths.*

The advent of organized religious faiths as a dominant political and social force, which occurred in the earlier centuries of our era, was a development by no means limited to Christianity. It was a world-wide phenomenon, showing many similar features in widely different regions, and indicating that it arose from a common need by virtue of common possibilities. Between the third and the seventh century A.D. we find the rise to power and influence of Christianity, of Islam, and of Buddhism in China and south-east Asia. Buddhism in India and Zoroastrianism in Persia were, it is true, founded as religions some seven centuries earlier, but it was in this period that their doctrines were fixed and their priesthoods organized. This was also when even the most multiform and unorganized religion, Hinduism, which was replacing Buddhism in India, established itself anew and codified its sacred books.*

It would seem as if, for the first time in human history, there was the need for religions based on a fixed system of beliefs together with the means of maintaining them. A clue to the explanation of the latter condition is given by some of the characters of organized religion, which in various degrees are found in all, or nearly all, of them. They are a hierarchic priesthood, fixed rituals, and as a test and rallying point a *creed* involving belief in an order of the universe, embodied in

sacred books. In addition there are auxiliary features which are more variable—the appearance of devotees—either singly as hermits, fakirs, yogis, or in bodies as monks, lamas, or dervishes—given over to asceticism, begging, preaching, or occasionally working. Certain of these practices are far earlier than organized religion, and indeed are found in the most primitive communities, but they took on a new aspect in relation to advanced city life. Hermits and monks represent the religious side of the flight from the oppressive and sinful cities in the period of their decay, the secular side being the retirement of the wealthy to their country estates to evade the imperial tax collectors.[3.1a]

The central feature of the new, organized religions is the social coherence of the Church and the creed it defines and imposes. It lies in common ritual and common philosophic beliefs. The fact that these religions are all, in Mohammed's phrase, "peoples of the book," shows that they imply a certain degree of literary culture in a numerous if restricted class. The fact that the ritual and ministrations of the Church are extended to all the people shows that at the same time the priesthood aim at securing a universal or *catholic* assent. The new religions were indeed, once they had outgrown their formative revolutionary phases, essential stabilizing organizations. They aimed, often unconsciously but sometimes consciously, at making the social order generally acceptable by showing it to be an integral part of an unchangeable universe (p. 717). At the same time the introduction of gods, myths, and visions of a future life provide distractions and a celestial balance to the injustice of this world.

Early Christianity

These features are particularly evident in the history of early Christianity. A knowledge of this history is of unique importance to the understanding of science, for it was within the framework of Christianity, except for a brief period under Islam, that modern science grew to maturity. Christianity arose out of the distress and aspirations of the common peoples of the Roman Empire (p. 167). It is no accident that it first appeared among the Jews, who were, if not the most oppressed, certainly the most rebellious of the subject peoples. Jesus himself, as a hoped-for Messiah, was taken for a revolutionary and suffered a revolutionary's fate. The early Christian communities were themselves, or were closely modelled on, those of

the Essenes.[3.36] These had been formed as closed, economically self-supporting, communist groups of Jews who rejected both the compromises with wealth and foreign customs, into which the originally revolutionary Maccabees had been betrayed (p. 109), and the ritual particularism of the Pharisees.*

This association with the Jewish democratic tradition and especially with the rejection of any compromise with the powers of this world assured early Christianity of popular support which was only reinforced by official persecution. The popular appeal of Christianity was at its greatest in its first two centuries, just at the time when the Empire seemed most safe and glorious to the wealthy and cultured citizens. It was then that Roman rule bore most hardly on the common man and the slave. For them there was no hope in this world and little reason to dread its fiery end. Christianity was able to spread far more widely than Judaism because it shook itself free from the tribal particularism of Judaism while preserving all of its popular appeal. It was something far more than just another mystery religion such as Mithraism, which also flourished mightily in that disturbed time. Christianity furnished an all-inclusive organization that, however outwardly submissive, was absolutely determined to have no part in the oppressive and sinful classical civilization. Inevitably it became a political movement, representing at the outset the aspirations of the oppressed lower classes in the great cities and a national reaction of the oriental peoples against dominant, upper-class Hellenism.

Christianity did not, however, long remain confined to the lower classes, and little by little, as it came to include more and more cultured proselytes, many of the ideas of the classical world crept into its teaching. Some were much more easily assimilable than others; in particular, Platonism and, even more, its half-Christianized off-shoot, Neoplatonism, which was so useful in emphasizing the "other worldliness" of religion. The two aspects—the popular revolutionary apocalyptic aspect of religion, with its vision of a Last Judgment and a Kingdom of God in our time; and the other-worldly spiritual attitude, very much more favoured by the upper classes—have run through the whole of Christian history to this day.[2.42a]

It would be wrong now, however excusable in Gibbon's day, to hold Christianity, as such, to blame for the economic or cultural collapse of classical civilization. The causes of this,

as has been shown earlier, were intrinsic. The Church, which was to play the dominant role in the subsequent Dark and Middle Ages, did determine, to a large extent, the character of the culture that it installed in its place. The Church was the one coherent institution of the late classical world that had survived the troubles of the fall of the Empire in the West. It had also, long before that fall was complete, penetrated far beyond the ancient bounds of the Empire to cover much of Europe from Ireland to the Caucasus and had spread widely into Asia. To an extent unparalleled since the days of ancient Egypt, culture and even literacy were confined to the clergy. The Church, in addition to its spiritual functions, provided for education, administration, and, in the early Middle Ages, for law and medicine as well.

Ecclesiastical organization

It was no accident that the Church survived the Empire; it had far more solid political and economic foundations. Beginning as a virtually revolutionary movement—true, with an other-worldly objective, but nevertheless openly antagonistic to civil administration—it early acquired in self-protection a close organization, part agitational, part economic. This organization at first through its elders—*presbuteroi*, priests—and their servants—*diaconoi*, deacons, deans—kept in personal touch with every individual Christian and could count on his support in a way no imperial official could hope to do. Later in the second century, as the Church grew in numbers, higher organization was necessary to ensure that doctrinal and personal quarrels did not split it into innumerable fragments. A parallel organization to the State was built up, often using the same terms such as *ecclesia*—eglise—church, *basilica*—royal palace, and *diocese*. Inspectors—*episcopoi*, bishops—were ordained, and later the most important of these became the great *patriarchs* of Jerusalem, Rome, Constantinople, Alexandria, and Antioch. Centuries passed before the bishop of Rome claimed the primacy as the Holy Father, the Pope, God's vicar on earth, the Pontifex Maximus or Chief Bridge-builder—once merely across the Tiber, but now between heaven and earth.[3.1a]

By the third century the Christian Church, though it still included only a small minority of the population, was the most powerful, widespread, and influential political organization in the Empire. Desperate persecutions failed to break it. By the

fourth century it became clear that the only way to save the Empire was to take the Church over, and Constantine, long before he became a Christian, took this final step in 312 A.D.

The end of paganism

Once the Church was in power, and disposing at the same time of patronage and punishments, the pagans, at least in the towns, were soon won over. There was, in any case, little resistance. The worship of the Olympians was by then not very serious and had only a snob value. As for philosophy, almost every school could be found in Christianity itself. What the Church could still not tolerate was any philosophy officially independent of Christian revelation. But it did not, however, usually suppress it directly. The murder of the mathematician Hypatia was not policy, but monastic zeal getting out of hand. More typical of the end of classical science was the closing of the schools of Athens by the great Christian emperor, Justinian, in A.D. 529. The last of the professors were allowed to go to the new university of the Persian emperor Chosroes, at Jundishapur (p. 188). They found this atmosphere too strange and the Emperor sent them back with a treaty stipulation that they should not be molested.

More significant for the future was the conversion to Christianity of the philosopher now known as John Philoponos (*fl.* A.D. 530), which occurred about the same time. The conversion was whole-hearted; on going over he joined a kind of Christian Action party in Alexandria, the " Philopoenes " or " trouble lovers," mainly occupied in " fighting against pagan professors and from time to time attacking the last temples of the Egyptian gods." In the end he went too far and became a hyper-trinitarian, a tritheist heretic. In his rejection of pagan philosophy, Philoponos even had the temerity to deny Aristotle's theory of motion and founded the doctrine of " impetus " which, after attracting some support from the Arabs and schoolmen (p. 221), was in the hands of Galileo to lead to the emergence of modern dynamics (p. 293).

5.3—*DOGMA AND SCIENCE*

The triumph of Christianity effectively meant that from the fourth century onwards in the West, and up to the rise of Islam in the East as well, all intellectual life, including science, was

inevitably expressed in terms of Christian dogma and, increasingly as time went on, was confined to churchmen. Between the fourth and the seventh centuries the history of thought over the area of the vanishing Roman Empire is the history of Christian thought.

In the early days of Christianity, science and learning had been associated with the hated pagan upper classes and looked upon with suspicion. But this attitude did not last. The human message of Jesus could hardly suffice the Church once it aspired to cultural pre-eminence. As the Gospel of St John shows, with its cult of the divine word, the logos-mystical Platonism was already at work in the foundations and indeed, in a more diluted form, it is already evident in the message of St Paul.[2.42a]

Orthodoxy and heresy

The fathers of the Church, particularly Origen (*c.* 185–253), a schoolfellow of Plotinus the founder of Neoplatonism, set about to incorporate the safer parts of ancient philosophy into Christian dogma. Much of it had already found its place there unconsciously. The task was nevertheless difficult, partly owing to the very different philosophy which underlies the Old Testament (p. 109). Inevitably it led to controversies in which each side claimed to be orthodox and accused the other of heresy. The great disputes and heresies of the fourth and fifth centuries which split Eastern Christianity, those of the Arians, the Nestorians, and the Monophysites, were largely on points of interpretation of Neoplatonist ideas of the nature of the soul and its relation to corruptible or incorruptible bodies.

These disputes were nominally settled by Councils of Bishops, implying a basic democracy in the Church, but usually the decision went in favour of the side that could win over the Emperor. The great Arian heresy of the fourth century on the nature of the Godhead was settled in this way at the Council of Nicæa in 325. There Athanasius imposed his implacable Trinitarian creed. Its triumph was not assured, however, until almost two centuries later when Justinian had defeated the Arian Goths.

By the fifth century a compromise between faith and philosophy was worked out by St Augustine (354–430), who produced a kind of composite between scriptural tradition and Platonism, with a strong flavour of predestination, derived

from his Manichean experience (p. 192), which was to dog Christianity and particularly Puritanism ever afterwards. This included the essentially Zoroastrian idea of the cosmic conflict of good and evil (Ormuzd and Ariman) with its associated ideas of the Devil and Hell-fire. The Augustinian compromise did not last; heresy followed heresy, and the work of suppressing them had to be done all over again in the Middle Ages (p. 215), and ultimately failed altogether in the Reformation.

The philosophies on which theology was based, though subject to dispute, were all readily assimilable to an other-worldly religion, while the sciences of observation and experiment were not. In the first place these were plainly unnecessary to salvation, in the second, by the mere dependence on the senses, they depreciated the value of revelation. The overcoming of this attitude was to be the work of many centuries, and was only to be achieved in an economic and social atmosphere very different from that of the decaying Roman Empire.

In all these religious disputes natural science was a certain casualty. Classical philosophy, especially in its latter days, was absurd enough. The Old and New Testaments were never intended as interpretations of Nature. They contain moreover mythical and philosophical interpretations of all ages from the most ancient Babylonian onwards, and are therefore intrinsically self-contradictory.[2.42a] To attempt to combine philosophy and scripture is a task defying all reason, and fatal to any clear understanding of Nature. Faith and reason cannot be reconciled without allegorizing the one or distorting the other—in either case discouraging honest thinking.

It is fashionable in these days to praise the Church for preserving the science of antiquity down to our times. The survival of science, as will be shown, has been due rather to its success, where faith failed, in coping with the real world. It has survived in spite and not because of the centuries of effort to subordinate it to out-dated and contradictory beliefs. As we shall see in case after case right down to the controversy on Darwinian evolution (p. 483), the acceptance of obvious solutions has been held up for scores of years because they could not be made to square with Genesis. To say this is not in any way to blame the Church or the clerics, who in their time did their best according to their lights, but only those who today ought to know better. If science advanced slowly in Christendom

until the time of the Renaissance it was primarily not because of the Church, but because of the economic conditions that maintained it so long in its obscurantist role. Under feudal conditions advance could not have been faster.

5.4—*THE REACTION TO HELLENISM*

Science in Syria and Egypt

The Arian heresy was followed by many others. Two of these, however, those of the Nestorians and Monophysites, are of particular importance because they gave a decisive impetus to a national anti-Hellenic movement in Egypt and Syria, because they helped science to spread throughout Asia, and because they paved the way for the triumph of Islam. Once Christianity had become the official religion of the Empire, latent national or regional independence movements were bound to rally round heresies. What the heresies were is not now a matter of great moment. In A.D. 428 the Syrian monk Nestor maintained that Mary should not be called the mother of God, as she was only the mother of the human and not of the divine nature of Jesus. He was condemned at the Council of Ephesus (A.D. 431) and thousands of Syrian clerics, monks, and laymen faced persecution in his support. In doing so they defied the hated Byzantine government, and asserted their dormant Syrian nationalism against the Greek officials and upper class. The persecution was too effective to be resisted within the bounds of the Empire—and many Nestorians crossed the boundary into Persia, where a vigorous culture was being promoted by the Sassanian kings. Despite the official Zoroastrianism, they were well received on account of their medical and astronomical knowledge, and were established near the King's court at Jundishapur, where they built a famous observatory. Nestorian monks penetrated the whole of Persia, made converts, and set up churches as far away as China.

Sixteen years later Eutyches of Alexandria (378–454), in his desire to avoid Nestorian heresy, went so far as to declare Christ's human and divine nature to be one and the same. This one-nature—Mono-physite—heresy was duly condemned by the Council of Chalcedon (A.D. 451) under imperial pressure. Virtually the whole of the Egyptian clergy and many in Syria and Asia Minor defied the ban. Christians in Egypt and Abyssinia remain Monophysite to this day.

Persecuted Monophysites fled to Persia and quarrelled with Nestorians there. They too shook the dust of Hellenism off their feet and built up a vernacular Syrian science for theological purposes. This involved translating major Greek philosophic works into Syriac and thus starting the first independent national offshoot of Greek science.[3.27] These developments coincided with a vigorous economic upsurge in Syria which carried Syrian merchants, as successful rivals to the Greeks, all over the Mediterranean, and as far as Britain as well as over large parts of Asia.

The flowering of Indian culture

For the 500 years that followed the collapse of Rome the centre of science was shifted to the east of the Euphrates. The fifth, sixth, and seventh centuries were an age of great cultural advance not only in Persia and Syria but also in India. Under the protection of the vigorous dynasties of the Chalukyas and Rastrakutas, an effete Buddhism was replaced by a renaissance of Hinduism, to which the magnificent temples of Elephanta and Ellora bear witness. There was also, and this is of the greatest importance for the whole world, a new development of science, particularly mathematics and astronomy, associated with the names of the two Aryabhatas and Virahamihira in the fifth century, and with Brahmagupta in the seventh. The basis here was Hellenistic science with some additions directly from Babylonia [2.35] and probably also from China.*

Hindu numbers: the zero

A decisive new development was made there about this time: the perfection of a *number system* with *place notation* and a zero—our modern so-called Arabic *numerals*, which made computation something any child could learn. It is significant that its first mention in the West was in 662 by Severus Sebockt, a Monophysite bishop in Syria. Another Syrian, Job of Edessa (*c.* 800), in a very fanciful style, after equating the nine digits with the nine choirs of angels (p. 227), explained the reason for the roundness of the zero in these terms: [3.25]

> The movement of numbering is completed in a kind of cycle. It is for this reason that the Ancients invented, as a first sign for this number (ten), the (empty) space between the forefinger and the thumb, formed in a circular way.

> Indeed when the numbers which we have with us reach a denary state they stop, and then turn back and mount up indefinitely.

Elements of Hellenistic culture, including science as well as art, penetrated in this period with Buddhism to China and even to Japan. There they blended with a still evolving old Chinese culture, whose contribution to the main stream of technology and science was, however, to come somewhat later (pp. 230 ff.).

The culture of Byzantium

Taken all in all, the sixth and seventh centuries, far from being the darkest of the Dark Ages, were a period of a growing world-wide civilization in which the heritage of Greece was everywhere engendering new beauty and new thought. This holds with limitations even for the surviving, and by then almost completely Greek, Eastern Empire of Constantinople. There, under emperors like Justinian (*c.* 482–565), there was a great revival in arts and techniques, as witness the mosaics and architecture of St Sophia. But although the tradition of Greek philosophy and science was preserved in the Byzantine culture, it lacked the power of growth. This was in part due to clerical obscurantism—it was in response to it that Justinian had closed the schools of Athens—but far more to the fact that the Greek tradition on its home ground was dead. It was old stuff, respected but not exciting, and it bore no relation to the current realities of monastic rivalries, palace intrigues, and the chariot races in the hippodrome.

The transmission of classical culture

The breakdown of classical civilization, like that of the old river civilizations 2,000 years before, was by no means an unmitigated disaster to science. The new civilization that gradually replaced it escaped some of the limitations which had previously choked the progress that had started so hopefully in early Greek times. The two transitions, however, differ in one very important factor. Whereas there was little conscious continuity and no feeling of parentage or respect between the culture of the early civilizations and that of Greece, there was between classical culture and that of Syria, of Islam, of medieval, and still more of Renaissance Europe a continuity based on written documents and a strong feeling of being the

heirs of the Ancients. The main thread of tradition had indeed never been lost; throughout the Middle Ages, Muslim and Christian alike had access to the works of many of the major thinkers of classical times. These works, as well as many others, were made available to a far wider audience in the Renaissance through the medium of printing.

It would be a mistake, natural enough in the time of the Renaissance but unpardonable now, to assume that all that happened then was the taking up again of classical culture where it left off, or even where it was at its best. What happened was something different and far more important. The civilizations that took over the classical heritage of science had a hard task to prevent themselves from being stifled by it. We have seen in the last chapter the low state of activity into which it had fallen even in the East. There was still, however, the vast store of knowledge to be found in books available to any with the desire or skill to read them. The Syrians and Arabs, and after them the medieval schoolmen and the humanists of the Renaissance, had to trace that store step by step back to its Greek originals, resisting as well as they could the temptation to accept what they did not understand as the holy and mysterious knowledge of the Ancients. That they managed to absorb and transform it at all was by virtue of their own vigorous cultural developments. The very rediscovery of the works of the Ancients was the effect, far more than the cause, of the spurts of intellectual activity that characterized the beginning of Islamic science in the ninth century, of medieval science in the twelfth, and of Renaissance science in the fifteenth century.

These advances were the easier because at each stage the new knowledge covered a much wider field of interest than the old. Late classical culture was limited both socially and geographically. Socially it had become an almost exclusively upper-class preserve and was consequently abstract and literary, for ingrained intellectual snobbery had barred the learned from access to the enormous wealth of practical knowledge that was locked in the traditions of almost illiterate craftsmen. One of the greatest achievements of the new movement which culminated in the Renaissance was to raise the dignity of the crafts and to break down the barriers between them and the learned world.

The geographical range of classical culture had largely been

limited to the countries of the Mediterranean and the Near East. Its very completeness formed a barrier to the use of the common stock of techniques and ideas of the other ancient cultures of India and China. With the breakdown of the Roman Empire the way was open to much wider exchanges and influence.

5.5—*MOHAMMED AND THE RISE OF ISLAM*

To these negative factors of release there was soon to be added another—the sudden appearance and rapid spread of a new world religion. The barriers of language, religion, and government that up to the seventh century had limited each culture to its own region were suddenly swept away over nearly the whole area of the ancient civilizations, stretching all the way from the Indus to the Atlantic. The advent of Islam, though determined in its particular form by the personal character of Mohammed, was by no means an inexplicable or even entirely unique phenomenon. The decay of the power of the Roman Empire did not affect its prestige, which long survived it, still less the influence of the popular religion of Christianity which gradually came to dominate it, and which spread further than that of its Church and creed. Nevertheless, unlike northern Europe, where no other culture had been known and where Roman power had long since lost its terrors, the peoples on the eastern fringe of the Empire were reluctant to adopt Christianity as too identified with an alien, hostile, or oppressive government. At the same time neither the official Zoroastrianism of Persia nor the local gods of Arabian and African tribes could compete with the intellectually coherent and emotionally stirring content of Christianity. The way was open for the formation of new synthetic prophetic religions, popularly based, and incorporating as much of Christianity as could easily be acceptable without submitting to its Church or accepting its doctrine.

The first of these attempts, the mission of Mani in the third century, had a lasting but limited success. Mani claimed to be the third and final prophet following Zoroaster and Christ, and carried a message of eternal salvation for the *predestined elect* and consolation in this life for the faithful who ministered to them. Mani was martyred in *c.* 276 and his followers persecuted in Persia, but their influence spread as far as China in the East and Provence in the West, and some of their doctrines,

especially that of predestination, entering Christianity through their most eminent convert St Augustine, were to reappear again in Calvinism (p. 260).

The mission of Mohammed between 622 and 632, arising among the already vigorous and expansive Arabs, who only had to face the weakened and divided Roman and Persian Empires, had a greater promise of success. It still remains an almost incredible achievement for one man. Mohammed swept away the old tribal gods and replaced them by one God, Allah. Islam made a brotherly appeal to all men, it had a simple but exacting personal ritual, a theology reduced to bare monotheism, and it gave a sure hope of a realistic paradise for the believer. All this was conveyed in a poetic book, the Koran, which was not only an inspiration but a manual of ritual, morals, and law. It commanded then and still commands the devotion of poor and rich alike.

There was in Islam no church or priests, only the need for a court—Musjid (Mosque)—for common prayers and for readers of the Koran—*imam*—who were at the same time preachers and expounders of the law. Islam was from the beginning a literate religion. The Koran is still the common text-book for all Muslim peoples. The Caliph was the revered successor of the Prophet, at first also a civil ruler, but the strength of the religion did not lie in authority, but in the widespread religious community of the faithful. The political evolution of the early religious kingdom followed at first the late Roman or Byzantine pattern of a wealthy and luxurious court, torn by intrigue and depending increasingly on a prætorian guard of foreign, usually Turkish, slaves. This led to a break-up of Islam after its first two centuries into more and more feudal principalities, which were to be an easy prey to the nomads of the great plains and even to ill-organized and quarrelsome Crusaders. The religion of Islam, on the other hand, was solidly based in the people and was to outlast all misrule and conquest. Even as Christianity did in the North, it was to convert its conquerors, and was to be spread over a large part of Asia and Africa, where it maintained a coherent culture which, though not progressive, has persisted to our day.

The rise of Islam was abrupt. Within five years of the death of Mohammed in 632 the armies of his followers had decisively defeated both the Roman and Persian armies. After that there was for many years to be no force that could resist them. By

the eighth century they had extended their conquests from Central Asia to Spain. The Roman dominions in Africa and Asia, with the important exception of Asia Minor, were in their hands as well as the whole empire of Persia, stretching right over Central Asia and into India. From that time on most of this vast area was to have a common culture, a common religion, and a common literary language. For some centuries it was to have a common government and free trade. For even longer religion and the pilgrimage ensured free passage from Morocco to China of scholars and poets.

The Arab Renaissance

The immediate effect was a great stimulus to culture and science. The Arabs were no strangers to civilization. They had their own cities and had fulfilled an essential function in organizing the eastern trade of the Roman Empire. The ease of their conquest showed that all they did was to take over the urban civilization of the Mediterranean with the effective consent of the inhabitants. By that time few of these were prepared to fight to keep up an imperial government which did little but impose heavier and heavier taxation for increasingly ineffective services. The fact that Christianity was now the official religion hindered rather than helped the resistance of the populations of the Asian and African parts of the Empire, who were largely heretics and were safer from persecution under the Muslim Caliphs than under the orthodox emperor.

The Arabs, apart from securing for themselves the revenues of magnates and officials, were not in the least inclined to interfere with the local or city economy. The whole of the administration of the Omayyad Caliphate of Damascus was carried out by Greek officials in Greek. There was accordingly no specifically Islamic economic system. It was simply a late classical urban economy with the military command reserved, at first, for pure-blooded Arabs, but later falling, as in Rome, into the hands of any effective adventurer. Slavery did not disappear but, for lack of supplies of slaves, it was largely reduced to domestic service. Where there was gang slavery there were mass revolts, and that of the negro Zanjs from the saltpetre works of the Persian Gulf proved as formidable as the Spartacists of Roman times. The land was tilled by heavily taxed *rayats*, virtually serfs. These also often rebelled. One

such rebellion, that of the communist Karmatians, maintained itself for over 100 years.

With reviving trade, merchants became relatively more important than in late classical times. Indeed the unity of Islam greatly helped trade by restoring the wide sphere that the Roman Empire had lost in the troubles of its latter years, and at the same time by extending and decentralizing it. In the whole area of the Moslem conquest, from Cordoba to Bukhara, there was no one centre which, like Rome, dominated and sucked in the economy of the Empire. Mecca was always a religious, not a political, economic, or cultural centre. Instead, not only did old cities, such as Alexandria, Antioch, and Damascus, take on a new lease of life, but also new cities on the same model appeared everywhere, particularly the great new capitals of Cairo, Baghdad, and Cordoba. All these cities were in constant communication with each other, and their varied products formed a basis both for trade and technical improvement.

Further, the cities of Islam were not isolated from the rest of the eastern world, as had been those of the Roman Empire. Islam became the focal point of Asian and European knowledge. As a result there came into the common pool a new series of inventions quite unknown and inaccessible to Greek and Roman technology. These included such manufactures as steel, silk, paper, and porcelain. In turn these formed the basis for further advances, which were able to stimulate the West to its great technical and scientific revolution of the seventeenth and eighteenth centuries.

The revival of classical science

On the intellectual side also there was very little break in continuity. The religion of Islam had at the outset, though not later, far less cramping effects on human thought than that of Christianity. By the time it appeared there was no danger to faith in paganism or philosophy. After the turbulent century of conquest even the leaders of Islam sought avidly for the old knowledge of the Greeks, and as much of their other culture as the Koran would allow them.

This impact of foreign influences coincided with the fall of the Omayyad dynasty of Damascus and the advent to power in A.D. 749 of the Abbasids, who, though not themselves Persian, depended on Persian support and liberated the traditional learning and science of that ancient and cultured people.*

Learned Persians, Jews, Greeks, Syrians, and a few from farther lands met in the new capital of Baghdad. It was there and in Jundishapur that began the translation into Arabic of the main books of Greek science.[3.27] These translations were made either directly from the Greek or, more often, from the Syriac, and the work was subsidized from the start by the Caliphs and notables. Caliph al-Mamun actually founded a bureau of translation, Dar el Hikhma, where the great scholars Hunain ibn Ishaac and Thabit ibn Khurra produced Arabic texts of most of Aristotle and Ptolemy. They also translated many Persian and Indian books, but these were not further translated into Latin and were thus lost to the West.

The books that were translated were nearly all of science and philosophy because, naturally enough, the Arabs had no particular interest in the history of the Greeks. As for Greek drama and poetry, this had relatively little to give to a people who had a rich source of legend and a living poetry themselves. It was largely as the result of this concentration of interest that when in turn Islamic knowledge came to be transmitted to the West, it was at first limited to science and philosophy. The humanities were for the most part rediscovered directly from the Greek and Latin authors only in the Renaissance. The fact that the sciences and the humanities entered modern culture by such different channels is an important factor in the development of science, and has had much to do with setting up the barrier between science and the humanities that persists to the present day.

5.6—*ISLAMIC SCIENCE*

It is difficult to estimate the value of the actual contributions to this fund of learning that were provided by Islamic scholars themselves. Certainly the learning of the Greeks was brought to life again and not merely transmitted without change. In fact it was subjected to a process similar to that undergone by the learning of the ancient East in the hands of the Greeks, though in this case the affiliation was far more direct and acknowledged. Because the Islamic scholars had no emotional identification with the old legends of the Greeks, they approached Greek learning with a much more detached attitude than the Greeks themselves were able to do. On reading Islamic scientific works one is struck by a rationality of treat-

ment that we associate with modern science. On the other hand the Muslims were equally, if not more, attracted to the mystical aspects of late classical philosophy, particularly Neoplatonism, which they at first were unable to distinguish from Aristotle, owing to the incorporation in his works of such forgeries as *The Theology of Aristotle* and *The Secret of Secrets*. Much of this mystical confusion was passed on through them to the medieval schoolmen. Another misfortune that was to dog not only Islamic but medieval science was the exaggerated respect that was paid to the works of the Greeks, and particularly to Plato and Aristotle. The fusion of the number magic of Plato with the quality hierarchy of Aristotle was a multiplication of nonsense from which Islamic science was never able to shake itself free. It is, however, interesting to notice that, though the two great mystifications of early science, astrology and alchemy, were also pursued by the Arabs, the greatest figures of Islamic science such as al-Kindi, Rhazes, and Avicenna explicitly repudiated the extravagant claims of these pseudo-sciences.

The social position of the scientists in early Islamic culture was not essentially different from what it had been in late classical times. With the coming of the Abbasid dynasty there was a short period between 754 and 861 under the Caliphs—al-Mansur, Haroun-al-Raschid, al-Mamun, and even under the devout al-Mutawahkil—when science was encouraged on a scale unequalled since the early days of the Museum at Alexandria. The Omayyad Caliphs at Cordoba (A.D. 928–1031) and the petty Emirs who succeeded them in Spain and Morocco, were no less attentive, and even in the decay of Moslem culture ambitious princes such as Saladin, Mahmud of Ghazni, and Ulugh Beg of Samarkand prided themselves on encouraging science. In addition, rich merchants and officials, such as the Persian family of the Barmecides (*c.* 750–803) and the three brothers Musa (*c.* 850), supported scientists and some were themselves interested in science. This secular and commercial background to Islamic science, however, marked it off sharply from that of medieval Christendom, which was almost exclusively clerical (p. 222). It resembled far more that of the Renaissance. It was this courtly and wealthy patronage that enabled the doctors and astronomers of Islam to carry out their experiments and make their observations. It also protected them, while it lasted, from the active disapproval of religious

bigots who suspected that all this philosophy would shake the beliefs of the faithful.

This association of science with kings, wealthy merchants, and nobles was immediately the source of its strength and ultimately of its weakness, since science became, as time went on, completely cut off from the people, who suspected that the learned advisers of the great were up to no good, and this made them an easy prey to religious fanaticism. As long as the cities and trade flourished there was a sufficiently large, cultivated middle class interested in science to ensure discussion and progress. As this broke down, however, the scientists became more and more wandering scholars, dependent on the varying fortunes of local dynasties. Even the greatest of them, Ibn Sina (Avicenna), was never granted any security. He served various Sultans in Persia and central Asia, sometimes as doctor, sometimes as vizier. At Hamadan he escaped by a feigned illness from mutineers who were demanding his head. Ibn Khaldun (1332–1406), the last of the great Moslem thinkers, was a refugee from Seville forced to take service wherever he could find it. In his time he was to negotiate with Pedro the Cruel in Spain and Tamerlane in Syria, both of whom offered to employ him [3.24] (p. 717).

The character of Islamic science

The scientists of Islam on the whole accepted and codified the late classical pattern of the sciences. They had little ambition to improve it and none to revolutionize it. As al-Biruni (973–1048) put it, "We ought to confine ourselves to what the Ancients have dealt with and to perfect what can be perfected." [3.3.376] Though individuals might specialize, science formed a unity cemented by philosophy. It comprised the twin disciplines of astronomy and medicine, united by a more or less admitted astrology which furnished the link between the outer big world of the heavens—the *macrocosm*—and the inner small world of man—the *microcosm*. Philosophy as such was suspect—it was difficult to reconcile it with the Koran. Pious Muslim scholars certainly attempted to do so but this was frowned on by the orthodox. Al-Ghazzali's (1058–1111) book, *The Destruction of the Philosophers*, was a warning of the futility of this attempt. Despite the spirited answer of Ibn Rushd (1126–98), the much-maligned Averroes, in his *Destruction of the Destruction*, the warning remained

effective, and inevitably forced the doctrine of two truths—a higher spiritual and a lower rational truth—which ultimately sterilized both in Islamic countries as surely as it had done among the Greek Christians. The ultimate failure to associate science with the enduring features of Muslim religion was probably a major reason for its withering away in the later centuries of Islam, which became culturally and intellectually static.

During the most flourishing period of Islamic science, in the ninth, tenth, and eleventh centuries, these considerations did not yet weigh heavily. Indeed one may suspect that religion was taken for granted by some of the greatest scientists, and not allowed to interfere with the pursuit of secular knowledge. The unity of science was further ensured by the tradition of encyclopædism, which drove all the great and a number of minor Islamic writers to compose comprehensive treatises like the *Compendium of Astronomy* of al-Fargani (Alfraganus) (d. *c.* 850) and the great medical collections—the *Howi, Liber Continens* of Rhazes (865–925), the *Canon* of Avicenna, and the *Colliget* of Averroes—which were still being used as text-books in seventeenth-century Europe.

This comprehensive tendency was all the more valuable because its wider inclusion of the knowledge of other countries gave Islamic science a distinct advantage over that of classical times. Not only were the Arabs able to make use of the Mesopotamian astronomical and mathematical tradition, which had continued unbroken since Babylonian times, but they consciously used the ancient knowledge of India and to a lesser extent that of China.

Mathematics

The central interest in astronomy for its philosophical and astrological implications carried with it a renewed interest in mathematics, as astronomy was almost the only field of mathematical application and encouraged the pursuit of both geometry and computation. Here Islamic mathematicians, owing largely to Babylonian and Indian influence, made their greatest advance. The manipulation of numbers which appeared, with Diophantus, late in Greek mathematics (p. 156) was further developed, helped by the general introduction on a large scale of the Hindu system of numbers, which was already known, though not much used, by the Syrians. This technical device

had almost the same effect on arithmetic as the discovery of the alphabet on writing. Before then, arithmetic, other than what can be done on the fingers or the abacus, was a mystery which only the most learned understood. With arabic numbers it was within the reach of any warehouse clerk; they democratized mathematics. The Arabs also incorporated the work of a series of Indian mathematicians on the means of dealing with unknown quantities which we call *algebra*. The word itself comes from the title of al-Khwarizmi's great compendium *Hisab al-Jabr w-al-Muqabalah* or " restoration and reduction " as a means of solving equations. The Arabs also developed much further another field of great importance both to astronomy and surveying, that of *trigonometry*.

Astronomy

In *astronomy* the Arabs carried on the Greek tradition, accepting, without searching criticism or any radical advance, the elaborations of Ptolemy (p. 157), whose *Almagest* (Megale syntaxis) they translated. If they did not add to theory, they did keep up without a break the astronomical observations of the Ancients. In particular the observatories of Harran, a city of Chaldean star worshippers, continued well into Abbasid times, protected from Islamic interference by the fiction that they were Sabean " people of the book." If a break had been allowed, the Renaissance astronomers would not have had some 900 years of observations behind them, and the crucial discoveries on which modern science rests might have been made far later or not at all.

Geography

Geography remained for Islamic scientists what it had been for the Greeks, a special branch of astronomy. Yet, while they made little theoretical advance, on the practical side they were able to add to the knowledge of the Greeks to such an extent that they laid the foundation of the modern geography of Asia and north Africa. This they owed to the wider range of the Islamic world and the decentralization of its culture—for learned men were to be found from Fez to Samarkand—and to the long journeys that were undertaken by traders and pilgrims to Mecca. The traders penetrated far outside the countries of Islam itself. Learned travellers like al-Masudi (A.D. 900–57)

went into Russia and Central Africa and all over India and China, and many of them wrote well-ordered and rational accounts of their journeys, far in advance of the legends and marvels of the medieval geographers of Europe. Al-Biruni in his great book on *India* gave not only a description of its physical features, but an account of the social system, the religious beliefs, and the scientific attainments of the Hindus in a way that was not to be equalled until the eighteenth century. Geography was not merely descriptive, it was also metrical. The Caliph al-Mamun (*fl. c.* 830) ordered two separate measurements of a degree of latitude to be made, a performance that was not to be repeated until the sixteenth century by Fernel in France (p. 277). Maps and charts were made and astronomical instruments used in navigation.

Islamic medicine

Islamic medicine, like Islamic astronomy, was a direct continuation of that of the Greeks. Added to it, however, was a knowledge of new diseases and drugs, which was made possible by the wider geographical spread of Islam. The doctors, not only Muslim but also Jewish, studied a great range of diseases and concerned themselves as well with questions of the effects of climate, hygiene, and diet, not neglecting the practical art of cookery. Serving as they did rulers and wealthy merchants, the prestige of doctors was very high and so were their intellectual standards. The great Islamic doctors like Rhazes and Avicenna were necessarily men of wide knowledge which ranged from astronomy for astrological purposes, through botany to chemistry, for the selection and preparation of drugs. The fact that nearly all the Islamic scholars were doctors, and practising doctors at that, had an important and not sufficiently recognized influence on their scientific and philosophic views.

Optics

One branch of medicine which was much developed was the study of eye diseases, probably because of their prevalence in desert and tropical countries. The surgical treatment of eye conditions led to a renewed interest in the structure of the eye. This was to give the Arab physicians the first real understanding of dioptrics (p. 158) in the new sense of the passage of

light through transparent bodies, and hence to lead to the foundation of modern *optics*. The lens of the eye was to point the way to the use of crystal (*beryllus—brillen*) or glass *lenses* for magnification and reading, particularly by the old. The device of mounting such lenses in frames as spectacles was to come later (p. 241). The *Optical Thesaurus* of Ibn al-Haitham (Alhazen) (*c.* 1038) was the first serious scientific treatment of the subject, on which all medieval optics was based (p. 223). Although improved on, it was not to be superseded till the seventeenth century. In the lens we have the first extension of man's sensory apparatus, to balance that of his motor capacity already achieved through the use of mechanics. It was to be the prototype of the telescopes, microscopes, camera, and other optical instruments of later times. If they had done nothing else, the Islamic doctors in founding optics would have made a decisive contribution to science.

The beginnings of scientific chemistry

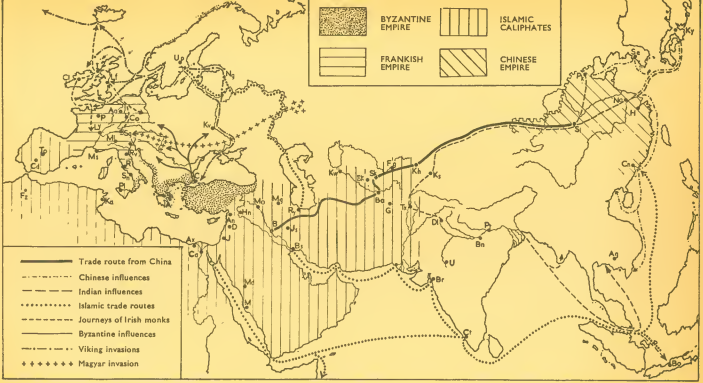
It was in chemistry, however, that the Islamic doctors, perfumers, and metallurgists made their greatest contribution to the general advance of science. Their success in this field was largely due to their having escaped, to a considerable degree, from the class prejudices which kept the Greeks away from the manual arts. Their treatises show a direct acquaintance with laboratory techniques in the handling of drugs, salts, and precious metals. The Arabs were not the first chemists, and worked on the basis of traditions and practices already deeply rooted in Egyptian and Babylonian civilizations and only slightly rationalized by the Greeks. They were also able to draw, to an extent difficult to ascertain, on the extensive chemical knowledge of the Indians and Chinese.[3.4] Chemistry, to a different degree from astronomy and mechanics, depends on widespread experience of large numbers of substances and processes. It can only become a science if these can be brought together and transmitted as a graspable whole, and provided with some general principles. This is what the Arabs did, and what justifies their claim to be the founders of chemistry.

One practical key to chemical advance, the still, had already been discovered in its earlier form of the kerotakis or alembic (ambix) (p. 160), but the Arab chemists much improved it and used it for a large-scale *distillation* of perfume[2.19] (Fig. 5). If

it had not been for the Koranic prohibition of wine they might have made the next crucial advance and distilled alcohol, but that was apparently left for the Christians. The wealth of new techniques, of which this was only one, was not, as was much of the technique of classical times, left to find its way into craft traditions. It was examined and discussed by the most able doctors and philosophers. Accordingly, it was possible for the first time to approach chemical transformation rationally, though, on account of its objectively greater complexity, never with the same simple analysis that sufficed for mechanics or astronomy.

Instead, chemical ideas originated from the actual method of thinking by analogy, that is essentially biological or sociological.* In chemistry there is a fundamental duality—which we now know is due to shortage or excess of electrons—exemplified by metals and non-metals. There is evidence for tracing the first appreciation of this duality to the Chinese, who already in prehistoric times used red cinnabar as a magic substitute for life blood and had resolved it into its elements, sulphur and mercury. Identifying these with the generalized male and female principles, the Yang and the Yin, themselves of totemistic origin, the Taoist sect developed a system of alchemy from which it is probable that first Indian and then Arabic alchemy was derived. It was originally not so much a method of preparing gold but the elixir of life.

The Arabs took up this mercury–sulphur theory and extended it.[3.38; 3.40] It was to be the gem of the spagyric theory of Paracelsus (p. 272) and, through him, first of phlogistic and then of modern chemistry. The earliest writings seem to have been lost or possibly incorporated in the pseudo-Aristotelian doctrine of dry and wet earthy exhalations, used to explain the origin of minerals. Similar ideas have been attributed to Jabir (Geber), who is supposed to have flourished in the eighth century and to be the father of Arabic chemistry. However that may be, there is certainly found in the works of Al-Razi (Rhazes), the greatest of Arab physicians, an extensive compendium of chemical operations and substances. The future of chemistry was indeed to depend on the first full-scale production in localized chemical industries in Islamic countries of such commodities as soda, alum, copperas (iron sulphate), nitre, and other salts which could be exported and used, particularly in the textile industry, all over the world.[3.38; 5.4]



MAP 2.—THE WORLD OF THE TRANSITION TO FEUDALISM, A.D. 550–1150 (CHAPTER 5)

This map brings out the relations of the different centres of civilization and the approximate extent of the empires as they were in the mid-eighth century. The Byzantine and Irish monastic influences came earlier in the eighth century; the Viking and Magyar raids later towards the end of the ninth. The towns marked, particularly in Central Asia, are centres of trade and science.

Aa—Aachen **Ax**—Alexandria **Ag**—Angkor **An**—Antioch **A**—Athens **Ba**—Balkh **B**—Baghdad **Bs**—Basrah **Bn**—Benares **Bk**—Bukhara **Bo**—Boro Budor **Br**—Broach **Ca**—Cairo **Ct**—Calicut **Cn**—Canton **Cl**—Clonmacnoise **Co**—Cologne **C**—Constantinople **Cd**—Cordoba **D**—Damascus **Dl**—Delhi **Fg**—Ferghana **Fz**—Fez **G**—Ghazni **H**—Hangchow **Hn**—Harran **I**—Iona **J**—Jerusalem **Js**—Jundishapur **Ka**—Kairowan **Ks**—Kashgar **Kh**—Khotan **Kv**—Kiev **Kw**—Kwarism **Ky**—Kyoto **Lf**—Lindisfarne **L**—London **Ly**—Lyons **Mg**—Maragha **M**—Mecca **Md**—Medina **Ml**—Milan **Mo**—Mosul **Ms**—Marseilles **Na**—Nanking **Ng**—Novgorod **Pl**—Palermo **P**—Paris **Pt**—Patna **Pk**—Peking **Rv**—Ravenna **Ry**—Ray **R**—Rome **Sg**—St Gallen **Sn**—Salerno **Sk**—Samarkand **Se**—Seoul **Sl**—Siao **Tx**—Taxila **To**—Toledo **U**—Ujjain **Up**—Uppsala **V**—Venice

The legacy of Islamic science

This bare outline can do but scant justice to the extent and weight of the Islamic contribution to science. Though in its central themes it is evidently a continuation of Greek science, the latter was both revivified and extended. By their renewed activity as much as by their search for earlier and better authorities, the Islamic scholars rescued Greek science from the decadent state that it had fallen into under the late Roman Empire. They created a live and growing science, even if at no point does it rise to the heights of the speculations of the Ionic Nature philosophers or equal the geometrical imagination of the Alexandrian school. By drawing on the experience of non-Hellenic countries, Persia, India, and China, they were, however, able to extend the narrow basis of Greek mathematical, astronomical, and medical science, to initiate the techniques of algebra and trigonometry, and to lay the foundations of optics. The crucial extension of Islamic science was to be in chemistry or alchemy, where they transformed old theories and added new experiment to create a new discipline and tradition of science. This tradition was often qualitative and mystical in character, but for that very reason was to be, for many centuries, an invaluable counterweight to the over-rational and mathematical, astronomical-medical tradition of the Greeks.

5.7—*THE DECAY OF ISLAMIC CULTURE*

After the eleventh century, although there was no spectacular collapse, it is evident that the best days of Islamic science were over. There were still brilliant individual scientists. One of the greatest, Averroes, dates from the twelfth century, and Ibn Khaldun comes as late as the fourteenth, but they are no longer part of a widely based and living movement. The failure of science is here only one symptom of a general political and economic decay of Islam in its original form. Essentially it was the delayed effect of the same social forces that had brought about the decay of classical culture. Neither in Islam nor in the surviving Eastern Roman Empire of Byzantium could the same inequalities in wealth fail in the long run to lead to economic breakdown. The Arabs, when they took over the Asiatic provinces of the Empire, inherited its problems as well as its wealth. The subjection of peasants and craftsmen

destroyed the market for an effective industry. This result could only be postponed by using up the considerable resources accumulated in the Byzantine Empire, and by opening new fields for commercial exploitation in Russia, Central Asia, and Africa.

In the end both the Byzantine and Islamic Empires were unable to maintain the organization necessary to control an extensive State. By the tenth century they both began to break up internally, and to grow more dependent for military, and then for economic, purposes on local efforts. By the time of the Crusades both had developed into a local feudalism which was inferior militarily, and culturally was no longer markedly superior, to that of the West. Further, the Eastern feudalism lacked, as we shall see, the economic resources and the cultural hopefulness of the new feudalism of the West. It lacked especially the widespread basis that was provided by the manorial village, with its living tradition of the old tribal collective.

The breakdown of Islamic civilization was undoubtedly accelerated by the arrival of new waves of barbarians from the Steppe lands. The Turks and Mongols by themselves, however, would never have been able to overrun the Islamic lands and effectively sterilize their culture by the thirteenth century, had these been in a flourishing economic state. As it was, the irrigation agriculture of Mesopotamia was largely ruined by a combination of native misrule and Mongol incursions which prevented the maintenance of the canals. That invasion alone is not a sufficient explanation is shown by the contemporary decline of Egypt and north Africa, into which the Mongols never penetrated, and the fact that similar incursions into the fundamentally more stable economics of China and India had no effect on their economies and little on their cultures.

Islam was to survive and survives to this day as a religion and a civilization, but it was not to regain the same scientific impetus that marked its first flowering. The equilibrium reached in the Mongol and Turkish States that succeeded the original Arab empires was one in which science stayed substantially frozen at the stage it had reached in the eleventh century. The ostensible reason for this was the rise of the clerical faction which actively discouraged philosophy and science. But this, had there been any real need for science, would in itself have been no more effective than it was in

Renaissance Europe. In the East, once the earlier stimulus to economic progress failed, the intellectual stimulus also vanished. Both might have revived later, but by the time they showed signs of this, as in India under the Moguls, their development was cut short by the superior commercial and military achievements of early European capitalism.

The fruits of Islamic science were, however, not wasted, though they were not to be enjoyed in the lands that cultivated them. To an extent far greater than that of the transmission of Greek science, the whole apparatus of Islamic science, data, experiments, theories, and methods were handed on directly to the new, growing science of feudal Christendom. Indeed, if this were a history of science instead of one of its influence, it would have been more logical to treat together as one chapter of intellectual advance the whole period from the seventh to the fourteenth century, hardly distinguishing the languages—Syriac, Persian, Hindi, Arabic, or Latin—in which the books were written. The difference between the new science of the sixteenth century and that of the thirteenth in Europe is far greater than that between Arabic and Latin science in the twelfth century. Both the glory and the limitations of Islamic and Christian science in the Middle Ages stem from the same root, their association with the political and economic basis of feudalism; but the demonstration of this must await the next chapter.

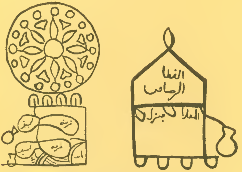


Fig. 5.—SKETCHES OF SINGLE AND MULTIPLE TOWER STILLS. The rose-like diagram represents the plan

(From al-Dimaschqi's *Cosmography* in E. Wiedemann, *Beiträge zur Geschichte der Naturwissenschaften*, XXIV. Erlangen, 1911.)

Chapter 6

MEDIEVAL SCIENCE AND TECHNIQUE

6.1—*THE DARK AGES IN WESTERN EUROPE*

WHILE a brilliant cultural development was taking place in the Eastern Empires and in Islam, most of Europe was still suffering from the confusion left by the collapse of the Roman Empire and by the barbarian invasions. Between the fifth and the ninth centuries towns decayed everywhere. In Britain, where they were alien foundations, they completely disappeared; in Italy, where they had 1,000 years behind them, they survived, though half ruined and deserted. The first barbarian rulers—Franks and Goths in the West, Slavs in the East—maintained a shadow of the Imperial system, including trade on a considerable scale in luxury goods and slaves. Classical culture gradually died out, leaving such living relics as the swan song of Boethius. The new Christian culture, preserving the scriptures and fragments of Latin and Greek literature, was spread from outlying centres such as Iona [3.1a] or Kiev.[3.21a] Only in Constantinople was a Christianized Empire, more Greek than Roman, able to maintain itself and to guard the Classical heritage.

The western kingdoms, despite their unification under Charlemagne, were unable to maintain a State organization on the Roman model against the treble attack of the Normans, Magyars, and Saracens. Nevertheless they were not overwhelmed, and emerged after a few years vigorous but fragmented. Their successful resistance was achieved on a basis of local defence and local self-sufficiency—the feudal system. Once this was well established, as it was from the year 1000, recovery was rapid. The very factors which had held up the early development of western Europe—its forests and heavy soils—made its advance more rapid when it came. From the tenth century onwards the intrinsic economic advantages of Europe began to tell. They were primarily agricultural, based on the suitability of western European climate and soils for dry cultivation once technical difficulties of cutting down woods and

ploughing heavy soils could be overcome (pp. 168, 233). The Islamic East, on the other hand, was for the most part an arid region. As such, it was liable to increased desiccation and erosion, and this became catastrophic when it was combined with the decay of the governmental organization which alone could maintain irrigation systems and keep the ravages of faulty agriculture in check.

No such requirement for extensive organization existed for western Europe; only local and not national effort was required. Even starting from a stage of extreme disorganization, its economy could rebuild itself village by village. Slowly but irresistibly a new civilization, which was soon to surpass its forerunners, arose on a solid basis of abundant, fertile, and well-worked land. Nevertheless only the western and northern parts of Europe were able for long to make use of these advantages. They were saved by their remoteness, and even more by their forests, from the last incursions of the Asiatic pastoral peoples. In the thirteenth century the Tartars overwhelmed the highly civilized State of Kiev. This Byzantine equivalent of Charlemagne's Frankish Holy Roman Empire was not entirely wiped out, but had to be recreated from its offshoots in the northern forests. As a consequence the Russian State came into action, as Great Muscovy, some centuries later than the west of Europe. In the fourteenth and fifteenth centuries the same fate fell on south-eastern Europe when the south Slav kingdoms and finally Byzantium itself were overrun by the Turks.

The world of medieval Christendom was thus a very limited one. Its central spine ran from Italy through eastern France to England; to the east it included only the Rhineland and the Low Countries; to the west, Gascony and Catalonia. Even in this area the most characteristic developments were more limited still, centring on the rich, well-watered agricultural plains of Flanders, Normandy, Champagne, and the Paris basin, and on the southern counties of England. It was in the land of the Franks, in the very Ile de France of which Paris is the centre, that the economic forms, the architecture, and the intellectual developments of medieval scholarship first came to flower. The other great cultural centre, that of Italy and particularly of Lombardy and Tuscany, was too impregnated with the influence of the classical world to produce such distinctive contributions. Its turn was to come in the later Middle Ages and the Renaissance (Map 3, p. 249).*

6.2—*THE FEUDAL SYSTEM*

In contrast to the slave economy of classical times that preceded it and that of capitalist economy that followed it, the economy of the whole period from the fifth to the seventeenth century may be taken as feudal (p. 180). Nevertheless it is only in Europe from the eleventh to the fourteenth centuries that the *feudal system* appears fully developed, complete with its political and religious hierarchies and with the corresponding art and knowledge.[3.20*]

The economic basis of the feudal system was the land. It was marked by its dependence on local agricultural production, largely consumed on the spot, and on a scattered handicraft industry. The economic unit in the feudal system was the *village*. There, some scores of men and women, mostly kinsfolk, shared out the land and work, holding most in common. They were not far removed in sentiment and sometimes even in ancestry from the old clan groupings. They carried out a simple rotation of crops, usually, in northern lands, with three fields divided into individual plough strips and some woods and pasture. On the peasants was superimposed a hierarchy of lords, lay or clerical, and their overlords, bishops and kings, under the nominal headship of emperor and pope. Each lord might hold one or more villages, or land in several villages, where his serfs were obliged to work to keep him as well as themselves. It is this obligation of feudal service, that is of work exacted by force or by custom backed by force, that distinguishes feudal exploitation from the wage-labour system of capitalism. It is the imposition of this obligation on peasants with secure tenure cultivating their own land that distinguishes it from the chattel slavery of classical times.

In theory, feudal obligations were not entirely one-sided. In return for the service of his peasants the lord was supposed to give them protection, but this should be understood rather in the gangster sense. For the commonest danger against which he had to protect them was the attacks of other lords. The whole duty of a noble lord was to fight for his overlord when called on, though he might fight against him when he felt like it. For the rest, he could eat and hunt. The whole duty of the spiritual lord was to pray, but he usually managed to consume as much provender to support him in this as his lay

brother. The higher nobility, lay and spiritual, together with their retainers, had for lack of adequate transport virtually to eat their way round their scattered manors. Even the king could never afford to stay in one place for long, but had to travel round with his court like a circus.[3.39] The nobility and clergy of the feudal system were little more than parasitic on the village economy. This parasitism, however, was thorough and intelligent. The bailiffs of the manor, lay or clerical, had learned well how to extract the last ounce of service and dues from the serfs.[3.39]

The fact that it was possible, without large-scale trade or organization, to maintain a parasitic class which with their unproductive retainers amounted to some ten per cent of the population, shows that the economy of the feudal village was far from primitive. Though in its social form it represents a return to a pre-classical village economy, it was a return on a higher technical level, with widespread use of iron, better ploughs, better harness, better looms, and the use of labour-saving devices such as the mill. The technical advances of classical times, which were concentrated in the cities and where production on the slave plantation villas was for the benefit of a plutocracy of traders and landowners, were, in feudal times, spread widely over the countryside, giving everywhere a local surplus. The feudal system was therefore, technically as well as socially, a far more secure base for further progress than was classical plutocracy.

At the same time, it was too locally subdivided and lacking in concentration to achieve this progress rapidly from its own internal initiative. What it could and did do, particularly from the eleventh to the thirteenth centuries, was to spread over the untilled and waste parts of Europe. This spread of land cultivation represented the only way in which feudal economy could develop without losing its character. It was pushed forward by nobles and churchmen alike, eager to enlarge their estates and power, and it was often supported by serfs as well because they could bargain for better conditions in the new lands. By the end of the thirteenth century this expansion overshot itself, and led to a serious economic crisis from which feudalism never really recovered.

Meanwhile, however, other economic forms were growing up inside the feudal system, based on a trading and urban manufacturing economy. These, by breaking down the local

self-sufficiency of feudal economy, were ultimately to destroy it; but at first they could be assimilated into the feudal system, which was to continue for another two centuries in Britain and Flanders, and for longer still in the rest of Europe. Feudal economy itself was largely a product of the disorganization produced by the collapse of the classical economy, and the barbarian invasions and disturbances this provoked. Once conditions settled down and warfare became merely occasional, tendencies to forms of organization not so directly based on the land reasserted themselves.

The medieval towns

Starting in the Mediterranean area, in south Italy, Provence, and Catalonia, where they had suffered least in the Dark Ages, and soon after in the Rhineland, the Low Countries, and Lombardy, where the agricultural surplus was greatest, towns began to grow again.[3.31] By the eleventh century towns were well established in these areas; by the twelfth they were also growing in northern France, England, and Germany east of the Rhine. As they grew they strove to emancipate themselves from the restrictions of Church and feudal institutions. In Germany and Italy, where central government was weakest, they became virtually independent city states; in France and England they remained subordinate to royal, though not to feudal, power. These towns lived by exchanging new manufactured goods, made by guilds of handicraftsmen within their walls, for the surplus products of feudal economy. The towns contained at first a negligible proportion of the population; even at the end of the Middle Ages in more urbanized countries such as Italy and Flanders they represented probably not more than five per cent. Nevertheless, their establishment was of crucial importance because it was from them that ultimately was to come the bourgeois (burgess) class that was to found capitalism. The same urban movement was also to be the focus of a new utilitarian science, radically different from that of the Ancients.

Throughout most of the Middle Ages, however, the towns had not this revolutionary role. Once they had achieved their necessary liberties they fitted very well into the essentially rural feudal economy. This economy, however, was by no means a stable one. In its first phase, as already indicated, the main emphasis was on the establishment and extension of

feudal order.[3.31] After the thirteenth century that order itself was beginning to break down not merely in Italy, where it had been least securely established, but at its centre in the Low Countries, England, and northern France. That breakdown was on the whole a progressive and not a degenerative one. It was marked by an increased production, not only of food but also of textiles, accompanied by a differentiation of peasantry in which the richer, at least, became emancipated from feudal service. Commodity production for the market took the place of subsistence economy, with a resulting enhancement of the importance of trade and towns. These were the conditions that gave still further impetus to the technical changes in manufacture and transport that were to lead to the new age of capitalism.

The impetus to technical innovation had, however, existed from the beginning of the Middle Ages, particularly in the better utilization of land and the increased use of machinery. It was here that the medieval peasant and workman could profit by the legacy of classical techniques and by the addition that the Arabs had made to them. What had been lost was largely, as already indicated, the arts of luxury and of large city organization. Aqueducts and baths could be done without, but mills and smithies remained. Agriculture and the practical arts were further improved, as we shall see, by borrowings from the East and by indigenous inventions. This improvement took the direction of a substitution of mechanical for human action; of animal and water-power for manpower. There was nothing, it is true, that the medieval craftsman could do that could not have been done by the Greeks or Romans, but they lacked the compelling incentive, the need to do more work with less men.

For most of the Middle Ages there was a chronic labour shortage. It was not only that there was no longer the expendable labour force of slaves that had held up technical advance in classical times. There was also the drive for extension of cultivation that stemmed from the nature of the feudal system. The nobles needed more and more land, but land was useless without peasants, and there were never enough of them, especially at harvest time. Of course, peasants could be made to work harder and hand over more of the produce to the lord, but there was a limit to this, forcibly demonstrated in peasant revolts. Hence the search, first by enterprising feudal

lords and ecclesiastics, then by wealthy merchants, for alternative methods of enrichment—for mills, for textile factories, for mines, and for foreign trade. Technical progress was slow, held up by the vested interests of nobles and guildsmen, but it could not be arrested, and its consequences in the end were to sap the foundations of the feudal system and the medieval world order which was its intellectual expression.

6.3—*THE CHURCH IN THE MIDDLE AGES*

The feudal system furnished the economic basis throughout the Middle Ages; its intellectual and administrative expression was provided by the Church. It was the unity and order of the Church that counteracted the anarchic tendencies of the nobles and provided for all Christendom a common basis of authority. Though on particular issues there was often a conflict of power between emperor and pope, king and bishop, both sides recognized the need of the other in the maintenance of society. The Church did not stand out against the feudal system, it was an essential part of it, and indeed one could not be changed without the other, as the Reformation was to show.

In the age of transition before the tenth century, the Church in the West was most concerned with the mere business of cultural survival. It was the one rallying ground of ancient civilization against successive waves of barbarians, Goths, Vandals, Franks, Saxons, and Lombards, which as they came into the pale of the Roman Empire had to be won to Christianity. Later the effort of conversion spread further, to the Norsemen and the Magyars. In all cases it imposed its rule in the first place as the heir to the greatness of the Empire, appealing to the ambition of barbarian chiefs and to the credulity and love of wonder of their households. In the process it was inevitable that the Church itself became barbarized; though it clung to the impressive externals of religion, the rituals, vestments, relics, and miracles, it lost much of its early intellectual content. What was saved was through the efforts of the remote early missions from Ireland and Northumbria, where monks such as Bede (673–735) and Erigena (*c.* 800–*c.* 877) preserved something of classical scholarship and philosophy.[3.1a]

The first general movement of intellectual recovery in Europe was that of Charles the Great, who, though himself illiterate, introduced palace schools in the ninth century; but that was

set back by new invasions of Norsemen, Magyars, and Saracens. It was only in the tenth century with the monastic reformation, starting at Cluny in Burgundy, that the Church seriously began to build an organization which could control the lives and thoughts of all the people of Christendom from king to serf. This organization was itself feudal, and indeed doubly so, for not only were the hierarchy of secular churchmen, popes, archbishops, bishops, and priests, all feudal landowners, but also the regular clergy, the monks, actually opened up land on their own account in their Abbeys and were the spearhead of feudal expansion.

All through the early Middle Ages, at least up to the beginning of the thirteenth century, even in Italy, the Church had in its priests and monks a practical monopoly of learning and even of literacy. Feudal administration had to pass through clerical hands, as the word clerk bears witness today. This monopoly was to give medieval thought a degree of unity, but it was also seriously to limit its scope. Neither Greek nor Islamic thought had been so confined to a single order of men (p. 197).

The professed attitude of the medieval Church to human affairs had been set in the dark days of the decay of the Roman Empire. It was that life in this world was a mere preparation for an eternal life in hell or heaven, an attitude which only gradually weakened with the undeniable improvement of human conditions, but was not to be blown away till the Renaissance. In practice, however, the Church took a shrewd interest in the affairs of this world, and was deeply involved in the maintenance of the feudal order.

The coming of the friars

This concern with an essentially rural economy set the Church, from the twelfth century onwards, in opposition to the interests of the secular society of merchants and artisans of the new towns. These expressed their dissatisfactions in heresies, usually of a Manichean and mystical kind, maintaining that man could approach God without the mediation of a host of greedy and ill-living clerics. Such heresies could be, for a while, put down by the sword, as in the great Crusade against the Albigenses in 1209; but by the mid-thirteenth century a more satisfactory solution was found. The Church secured a new arm in the licensed beggars and preachers—the Franciscan and Dominican friars—who had come into existence partly as an expression of, and partly as a reaction to, the changed conditions.

St Francis of Assisi (1182–1226) reflected in his life and preaching the revolt of the poorer townsmen against worldliness and excessive wealth. His message was popular, dangerously so, and all of papal diplomacy was needed to keep it from breaking out in heresy and civil strife. Such difficulties are still found today in the handling of "worker priests" in France. Even after the resistance of the "spiritual" Franciscans had been broken in 1312, their doctrine continued to work through Occam (d. *c.* 1349) and Wycliffe (*c.* 1324–84) and paved the way for the Reformation.

The friar preachers of St Dominic were, on the other hand, deliberately reactionary from the start. Their ostensible aim was to use persuasion to check the spread of heresy. The townsmen were becoming intelligent, even learned, and the greatest weight of orthodox learning had to be massed against them. Hence the philosophic labours of St Albert (1193–1280) and St Thomas Aquinas (*c.* 1227–74); hence also their instinctive sympathy with Aristotle, the great defender of order. How effective this persuasion was, as compared with the more brutal efforts of the Crusades and the Inquisition, it is difficult to tell, but heresy was kept down for some 300 years.

Nevertheless, despite the efforts of the friars, the last two centuries of the Middle Ages were to witness a definite weakening of the Church under the influence of the rising towns and the growing strength of the kings, who were increasingly allying themselves with the towns against the country nobility. The papacy was forcibly moved to Avignon in 1309 and the Church was split between two or three popes from 1378 to 1418. In healing this breach new authority was vested in general councils. Even these could not keep order, and though they could burn Huss in 1415, his followers defied them and maintained an independent national State in Bohemia until 1526. The Church, however, was only weakened as an organization; it had so impressed its stamp on intellectual and social thought that the disputes in politics and science of the next few hundred years were to be carried out mainly in terms of religion.

6.4—*THE SCHOLASTICS AND THE UNIVERSITIES*

The revival of western Christendom which began in the tenth century required an intellectual basis wider than was provided

by the meagre salvage of classical lore, even where transmitted by such able thinkers as Bede and Erigena. The clergy had to be trained to think and write; the claims of the Church, spiritual and temporal, had to be asserted and defended. At first this need was met by the setting up of cathedral schools such as those of Chartres and Rheims. By the twelfth century these had swelled to become *universities* with set courses teaching the seven liberal arts, philosophy, and, most important of all, theology. The first and most famous of these, the university of Paris, was not so much founded as recognized by 1160. The idea of a university—*studium generale*—where all subjects could be studied together was not entirely a new one. In antiquity there had been the schools of Athens and the Museum of Alexandria; the Muslims had had their Mosque schools, Madrasseh, for centuries, where philosophy as well as religion had been taught; and already, since the eleventh century A.D., a medical school had been in existence in Salerno. Though the new medieval universities were to borrow from all of these, they were more general and systematic in their teaching, and early acquired a special place in the world of Christendom as repositories of learning. Bologna was founded as early, if not earlier, than Paris; Oxford, practically a branch house of Paris, in 1167; Cambridge in 1209. Then came Padua, 1222, Naples, 1224, Salamanca, 1227, Prague, 1347, Cracow, 1364, Vienna, 1367, and St Andrews, 1410.

From their very foundations the universities were, and remained until relatively recent times, mainly institutions for training the clergy. This emphasis mattered little at a time when the clergy had the monopoly of literate occupations and were responsible for all administration. What was important then was that they should be educated at all, and particularly that they should absorb something of the ideas of the classical world. The teaching was by means of lectures and disputations, for books were scarce. This was still the method when faculties of medicine were added. The curriculum was fixed on the basis of the seven liberal arts, a summary, excessively simplified, of classical learning. The first three "trivial" subjects were grammar, rhetoric, and logic, aimed at teaching the student to talk and write sense—naturally in Latin. Then followed the "quadrivium" of arithmetic, geometry, astronomy, and music. Only after this study could philosophy and theology be approached. It is significant to note that the basic study was

not only secular but scientific; in this it followed the Islamic model. Law and medicine were catered for in other faculties, but neither history nor literature found any place. It was this omission which was to occasion in the Renaissance the humanist reaction against the whole scholastic system (p. 259).

In practice the science taught amounted to very little.[3.2] Arithmetic was numeration; geometry the first three books of Euclid; astronomy hardly got further than the calendar and how to compute the date of Easter; and the physics and music were very remote and Platonic. There was little contact, and little desire for it, with the world of Nature or the practical arts, but at least a love of knowledge and an interest in argument was fostered. In the latter Middle Ages the universities, with few exceptions, such as Padua (p. 267), had come to be guardians of established knowledge and barriers to any cultural advance, but in their early days they were the focus of intellectual life in Europe.

The impact of Arab and Greek knowledge

It was into this world of restricted and avid intellectual activity that there came the impact of Arab scholarship, carrying with it a far richer draught of classical knowledge than had even been preserved in the West. Beginning with a few works in the eleventh century it came in a full flood in the twelfth, when the bulk of Arab and Greek classics were translated into Latin, mostly from the Arabic,[3.2] but some directly from the Greek. Most of the translation was done in Spain, some in Sicily. The Crusades had a negligible influence on the spread of culture. This cultural transmission was of a character entirely different from those of earlier times except, perhaps, of that between Indian and Islamic science. For here, instead of the passing on of a practically defunct tradition to a new and vigorous culture, there was a handing over of the fruits of a culture hardly past its full vigour. At first sight there might have seemed to be enormous difficulties in the transmission of ideas expressed in a radically different language, and coming from people with religious beliefs not only foreign but actively hostile. These obstacles, however, proved to be superficial compared to the underlying similarity of the culture transmitted by the Arabs to that already held by the Latins. They were, in fact, only receiving more amply and from closer to its source the Hellenistic culture that was already the basis of their own.

Both contained the same substratum of Platonic and Neoplatonic thought. The words were unfamiliar but the meanings were not.

Not only that, but the very religion of Islam had been faced with the same intellectual problems—of the creation of the universe; of the reconciliation between faith and reason; of the literal inspiration or the eternal existence of the Koran; of the validity of mystical experience—that were to perplex the Christians. Duns Scotus and Thomas Aquinas were to continue the dispute already opened between al-Ghazzali and Averroes (p. 198). In terms of science alone, it would be logical to treat the period from the ninth to the fourteenth century as a unitary Arabic–Latin effort to reconcile religion and philosophy and complete the Classical world-picture. But this would be to ignore geographical and economic differences that were to bring about a decisive divergence in the consequences of that enterprise. For while in Islamic countries a compromise was reached which sterilized the advance of science, in Christian hands the dispute went on until, under the impact of economic changes, the whole Greek world picture was destroyed and replaced by another.

Faith and reason

Already in the eleventh century, before the full impact of Arab learning was felt, the disputes of the schools had been turning to this central problem of providing a basis for faith in reason or, more narrowly, of reconciling the scriptures and the fathers with the logic of the Greeks. At first this seemed easy enough: St Anselm (1033–1109) proved the existence of God from that of the idea of perfection. The details of a rational religion, however, were more difficult to fill in. Abelard (1079–1142) indeed presented, in his *Sic et Non*, respectable citations from the fathers expressing opposite opinions on almost every vital question. It seemed at first that the recovery of the major works of Aristotle in the twelfth century would provide sufficient guidance to solve these problems. Indeed his legendary reputation was more than justified when it became possible to appreciate the extent of his knowledge and the rigour of his logic. Moreover, as we have seen (p. 143), the essentially conservative doctrines of Aristotle had been originally made to fit a static, class-divided society. It only needed certain alterations to adapt them to a Christian, feudal, rather than a pagan, slave economy.

The first steps had already been taken by Averroes (p. 198), revered throughout the Middle Ages as the great commentator, but he had too much respect for Aristotle for his version to be readily adaptable to the Christian revelation.[3.19; 3.35] That task was achieved by the Dominican friar, St Thomas Aquinas. His great *Summa Theologica* provides an explanation of the universe of Nature and of man as a framework of the far more important drama of divine governance and human salvation. The whole is arranged in admirable system, with citations for and against every point discussed, together with an argument which always leads to the orthodox solution. Faith is always superior to reason, in the sense that there are things that reason alone could never discover, but equally revelation and reason can never be in conflict. The answers being known in advance, the Saint's arguments often have the air of special pleading. Nevertheless they have never been improved on, and form the basis of Catholic doctrine to this day (*n.*, p. 148).

Given the limitation of the time, St Thomas' performance was a remarkable feat of system and ingenuity, for it is more than a mere adaptation of Aristotle: it includes the use of the Aristotelian method to deal with situations of feudal society, which the Greeks could never have come across. Nevertheless it marks no original advance in thought, and to take it today as a philosophic basis is a confession of the intellectual bankruptcy of the neo-Thomist supporters of reaction.

St Thomas, indeed, was too able. Not only did he reconcile with reason the fragmentary and often contradictory doctrines of early Christianity but he used the Neoplatonic forgery, the *Celestial Hierarchy* of the so-called Dionysius the Areopagite—which, to be fair, was taken as gospel by nearly all medieval thinkers—as the major basis for his world order, which is accordingly no more Christian than it is scientific.

Some recent historians, impressed with the fact that modern science arose out of medieval scholasticism, have praised the quality of argumentation that enabled the schoolmen to do so. Now in the first place it was not the schoolmen who created modern science, but men like Leonardo, Bacon, and Galileo, who violently repudiated their aims and methods (pp. 303 f.). Further, the history of the scientific revolution shows that the removal of the accretion of nonsense of all ages was far the most difficult and tedious task in the foundation of science. When we realize that it took the best part of 1,000 years to carry

out the amount of thinking that, without these obstructions, could have been packed into 200, we may feel less inclined to revere those who established the doctrines that so effectively held back the advance of science.

The nominalist opposition

The labours of St Thomas were less kindly received in their times than they were to be long after. Even before the impact of Arab knowledge, there had been an opposition to the highly general method of argumentation based on the *reality* of Platonic ideas or Aristotelian substantive forms. The arguments of Roscellinus (*c.* 1050–*c.* 1122), the first of the *nominalists,* as opposed to the realists, were reinforced despite St Thomas by the Franciscan Duns Scotus (*c.* 1266–1308). The nominalists in effect, by asserting the importance of individuality and maintaining that things came before names or ideas, effectively rejected the whole rational theological scheme. Because they were also good Christians this did not lead them into scepticism, nor for the most part into a direct study of Nature, but rather, like al-Ghazzali, into an assertion of blind faith mystically held and so superior that human reason cannot hope to grasp it. Nevertheless, because they needed to dispute with realists, they had to develop their reasoning in a critical sense, and thus provided arguments that were to be of use in the later revival of natural science. William of Occam's famous razor "Entities should not be multiplied without reason" or more authentically "It is vain to do with more what can be done with fewer" has served to remove a lot of nonsense from scientific theory. Later still the school of Buridan (*c.* 1297–1358) and Oresme (1320–82) in Paris used Occam's methods to criticize Aristotle's doctrine of motion, and thus prepared the way for Galileo's reformation of dynamics (p. 293).[3.1; 3.2] In chemistry, where reason for long had a most tenuous hold, the alchemical approach also found support from the mystically minded. Raymond Lull (*c.* 1235–1315) of Majorca, who was the major source for the introduction of Islamic Sufic mysticism into Christendom, was, or was reputed to be, one of the founders of the chemical tradition which, as will be shown (p. 272), was to run through Paracelsus and van Helmont to the chemistry of the present day.

6.5—*MEDIEVAL SCIENCE*

This long theological, philosophic preamble to medieval science is necessary because what little scientific investigation there was in that age was undertaken almost exclusively for religious ends and by clerics—priests, monks, or friars. In this it is in marked contrast to the conditions of Islamic science, where few of the scientists had any religious calling and most had frankly utilitarian ends (p. 197).

The present fashion of extolling the science of the Middle Ages to the detriment of that of the Renaissance is a particularly silly one. Inaccurate in fact, it is especially unfair to the medieval cleric and scholar, giving him credit where he did not seek it and obscuring his real contribution. Even Roger Bacon (*c.* 1235–1315) in his ill-tempered and perverse denunciations of his contemporaries—he treats the great St Albert and St Thomas as " ignorant boys "—would never have questioned that the main end of science was the buttressing of revelation.[3.42] His only difference from them is that he sought his confirmation in experience instead of reason. The men of the Middle Ages were perfectly competent in reasoning and in the design and carrying out of experiments. These experiments, however, remained isolated and, like those of the Greeks and Arabs, were essentially demonstrations leading to no decisive advance. Much as they deserve credit for their achievements, the handful of medieval experimenters did not make much use of these methods to investigate Nature and less to control it. They had no incentive to do so and plenty of reasons to dissuade them. Being churchmen they had many other preoccupations: Gerbert (*c.* 930–1003), the first of the western scientists, became a pope; Robert Grosseteste (*c.* 1168–1253), the ablest of them, was a bishop and a chancellor of Oxford University; St Albert the Great was a provincial of the Dominican order responsible for the whole of Germany, so was Dietrich of Freiburg (*fl.* 1300), the best experimenter. Even the most daring thinker of the late Middle Ages, Nicholas of Cusa (1401–64), was drawn into papal propaganda and ended as bishop of Brixen. Anything they did in science was spare-time work.

The exceptions, Roger Bacon and the mysterious Peter the Pilgrim, prove the rule. Roger Bacon spent a large fortune on scientific researches and despite the Pope's blessing was put

in prison for his pains. Peter the Pilgrim was a pioneer in the experimental study of magnetism, on which he published one short letter (p. 235). According to his admirer Roger Bacon, " He does not care for speeches and battles of words but pursues the works of wisdom and finds peace in them " (p. 229).

The sum total of the medieval achievement in the natural sciences can be put down as a few notes on natural history and minerals by St Albert, an important treatise on sporting birds by the Emperor Frederick II, some improvements in Alhazen's optics by Dietrich of Freiburg and Witelo, including an account of the rainbow that was not to be bettered till Newton, and some not very original criticisms of Aristotle's theory of motion by Buridan and Oresme.[3.2] On the strength of this it is now asserted that the scientific revolution should date from the thirteenth century and that St Albert, somewhat belatedly canonized in 1931, has the right to be patron saint of science.

Mathematics and astronomy

In mathematics and astronomy, though the showing is better, it is essentially the same story. Fibonacci (*fl.* 1202), Leonard of Pisa, introduced Arabic algebra and Indian numerals into Christendom. He was a considerable mathematician himself but left no school, and mathematics made no serious advance till Renaissance times. In mechanics, Jordanus Nemorarius (d. *c.* 1237), in a rather simple account of the theory of the lever, advanced the principle of the equality of work done by a machine to that impressed on it, but this had and could have no effect on actual mechanics given the state of technique of the time.

In astronomy Ptolemy's *Almagest* was translated from the Arabic by Gerard of Cremona in 1175. Its study, together with the tables of up-to-date observations composed on the basis of earlier Arabic observations at the order of King Alfonso the Wise in the thirteenth century, made possible the continuation of Hellenistic astronomy in Christendom. There, as in Islam, it was of use mainly for calendaric and astrological purposes. It is worth noting that in observational astronomy, the only science where accurate observation, calculation, and prediction were necessary, Islamic predominance lasted longer than in any other branch of science. The Ilkhanic tables of Maragha (*c.* 1260) and those of Ulugh Beg (1394–1449) were the best

a

b

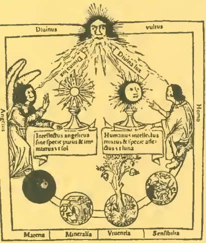


FIG. 6.—MEDIEVAL PRACTICE AND THEORY

(*a*) The astrolabe as used: " To knowe every tyme of the day by liht of the sonne, and every tyme of the nyht by the sterres fixe . . ."

From a manuscript of Chaucer reproduced in *Early Science in Oxford*, Vol. 5.

(*b*) The great chain of being.

The divine light illumines both angel and man, who are connected by the kingdoms of unformed matter, minerals, plants, and sentient beings.

From Bovillus's *De Intellectu*, 1510.

available until the Renaissance. The medieval astronomers showed themselves capable of making some improvements in detail in astronomical calculations, particularly the school at Merton College in the fourteenth century.[3.21b] They also made contributions to trigonometry and the construction of instruments. The most important of these was that of Levi ben Gerson of Provence (1288–1344), who popularized the cross staff, a kind of primitive sextant, which served the navigators of the voyages of discovery of the fifteenth and sixteenth centuries. It is interesting that apparently the first serious scientific work in English is the recently discovered *Equatorial Planetarie*,[3.32b] a mechanical device for predicting planetary positions, described though not invented by Geoffrey Chaucer (*c.* 1340–1400), whose *Treatise on the Astrolabe* "for little Lewis my son" has long been known.[3.15] There was no radical revision of astronomy, for though the opposition—impetus—school of Albert of Saxony (*fl. c.* 1357), Oresme and, most clearly, Nicholas of Cusa dared to suggest that it was the earth and not the heavens that turned daily, they did so on philosophic grounds. They were not astronomers themselves and professional astronomers continued to follow Ptolemy till well into the seventeenth century.

The limitations of medieval science

Though the contribution of medieval Christendom to science may have been unfairly ignored in the past, the danger today is rather to exaggerate its importance to the extent of making the whole history of science unintelligible. The significant fact is that as a live tradition it flourished only in the twelfth and thirteenth centuries and had by the early fifteenth lapsed into obscure pedantry which justifies and explains the contempt of the men of the Renaissance for Gothic barbarism.[4.27] This fact, coupled with the practical identity of the subjects treated and the methods used by the schoolmen with those of Islamic science, point to the conclusion that medieval science as a whole must be treated as the end rather than the beginning of an intellectual movement. It was the final phase of a Byzantine–Syriac–Islamic adaptation of Hellenistic science to the conditions of a feudal society. It arose as a consequence of the breakdown of the old classical economy and was in turn to decay and vanish with that of the feudal economy that succeeded it.*

It is unfair to expect more of such a science than what was demanded from it in its time. Both for the Muslim and the Christian natural science had a share, and not a very important one, in the great task of justifying the divine order of the universe, whose main features were given by revelation and supported by reason, that is by abstract logic and philosophy. Robert Grosseteste, probably the medieval scholar with the finest mind and with the greatest influence on the development of medieval science, thought of that science essentially as a means of illustrating theological truths. His study of light and his verification by actual experience of the refraction of lenses were undertaken because he conceived of light as analogous to the divine illumination (Fig. 6).[3.16]

Those who thought otherwise in the Middle Ages, and there were very few of them, were likely to be prosecuted for heresy or at best ignored. Here again Grosseteste's pupil, Roger Bacon, the most authentic voice from that time preaching a science for the service of man and prophesying the conquest of Nature through knowledge, proves how far we have come from the medieval outlook. Though he predicted motor ships, cars, and aeroplanes, and an alchemical science " which teaches how to discover such things as are capable of prolonging human life," his interest in science was essentially theological. For him scientific knowledge is only part, with revelation, of an integral wisdom to be contemplated, experienced, and used in the service of God.

The overriding need was to justify the truths of Christianity, as pointing to the true *end* of human existence on earth. No mundane knowledge could be compared to that of the scheme of salvation to which the Church, with its sacraments and traditions, held the key. It was such considerations that directed medieval thought to the ordering of all knowledge and experience to build one majestic world-picture containing in essence all that it was important for man to know. This encyclopædic tendency reached its height in the Middle Ages, not only in the complete logical scheme of Thomas Aquinas' *Summa*, but also in other works containing more general information like those of Bartholomew the Englishman (*fl. c.* 1230–40) and Vincent of Beauvais (d. *c.* 1260) whose *Speculum Majus* was not equalled in length until the French *Encyclopédie* of the eighteenth century (p. 371).

The medieval world-picture

It is necessary to say something here of this medieval world-picture if only because modern science arose largely out of the attempt to supersede it, and still bears many of the signs of the struggle. The main characteristics of the Græco-Arabic–medieval system were those of completeness and of hierarchy. The ethereal, cosmological scheme of Aristotle (p. 142) and the Alexandrian astronomers (p. 156) had become a rigid, theological–physical world, a world of spheres or orbs—the spheres of the moon and the sun; the spheres of the planets; above all the great sphere of the fixed stars beyond which lay heaven; and, as a theologically necessary counterweight, the underworld, the circles and pits of hell so grimly described in Dante's *Inferno*. The world was ordained as one of rank and place. It was a compromise between the Aristotelian picture of a permanent world and the Jewish and Christian picture of a world created by one act, only to be destroyed by another. It was an interim world which, though it had its own rules, was there merely as a stage for the playing out of each man's life on which depended his ultimate salvation or damnation.

Hierarchy

The hierarchy of society was reproduced in the hierarchy of the universe itself; just as there was the pope, bishops, and archbishops, the emperor, kings, and nobles, so there was a celestial hierarchy of the nine choirs of angels: seraphim, cherubim, thrones; dominations, virtues, and powers; principalities, archangels, and angels (all fruits of the imagination of the pseudo Dionysius). Each of these had a definite function to perform in the running of the universe, and they were attached in due rank to the planetary spheres to keep them in appropriate motion. The lowest order of mere angels that belonged to the sphere of the moon had naturally most to do with the order of human beings just below them. In general there was a cosmic order, a social order, an order inside the human body, all representing states to which Nature tended to return when it was disturbed. There was a place for everything and everything knew its place. The elements were in order—earth underneath, water above it, air above that, and fire, the noblest element, at the top. The noble organs of the body—the heart and lungs—were carefully separated by the diaphragm from the inferior organs of the belly. The animals and the

plants had their appropriate parts to play in this general order, not only in providing man with necessities, but even more by furnishing him with moral examples—the industriousness of the ant, the courage of the lion, the self-sacrifice of the pelican. This tremendous, complex, though ordered cosmos was also ideally rational. It combined the most logically established conclusions of the Ancients with the unquestionable truths of Scripture and Church tradition. The schools might differ on some of its details but none doubted that it was substantially a true picture. The essential problem had, as it seemed, been solved for all time. It was possible to have a universe which was at the same time practical, theologically sound, and eminently reasonable.*

6.6—*THE TRANSFORMATION OF MEDIEVAL ECONOMY BY NEW TECHNIQUES*

In the light of this it is easy to see how an attack on any part of the universal picture was considered to be something much more serious than a mere intellectual adjustment, but rather an attack on the whole order of society, of religion, and of the universe itself. It was therefore necessary to resist it with all the power of Church and State. The medieval system of thought was necessarily conservative and if it had been left to itself it would probably have been conserved to this day. But it was not left to itself. However much the medieval system of thought might tend to be static the medieval economy could not stay still.

The feudal system, as has already been explained (p. 211), contained the seeds of its own transformation. Greater trade and improved techniques of transport and manufacture drove relentlessly towards a commodity and money economy in place of one based on prescribed service. It was the technical aspect of this economic revolution that was to be the decisive factor in creating a new, progressive, experimental science to take the place of the static, rational science of the Middle Ages. It was to present the men of the Renaissance with situations and problems that the old knowledge was inadequate to deal with.

These intellectual adjustments consequently belong to the later period, but the essential technical changes themselves took place during the Middle Ages and indeed represent their most significant contribution to the scientific civilization of the

future. In such an apparently well-ordered and static society these technical changes remained for long unrecognized because they were for the most part beneath the notice of the clerical chroniclers, though they appear prominently enough in manorial accounts and lawsuits. We have one precious document in the note-book of a master mason, Villard de Honnecourt (*c.* 1250),[3.2] containing accounts and drawings of many mechanical devices. Very few of the medieval scholars mentioned technical matters and fewer still tried to understand them. How exceptional such an interest was is shown by Roger Bacon's eulogy of Peter the Pilgrim: [3.16]

> He knows natural science by experiment, and medicaments and alchemy and all things in the heavens or beneath them, and he would be ashamed if any layman, or old woman or rustic, or soldier should know anything about the soil that he was ignorant of. Whence he is conversant with the casting of metals and the working of gold, silver, and other metals and all minerals; he knows all about soldiering and arms and hunting; he has examined agriculture and land surveying and farming; he has further considered old wives' magic and fortune-telling and the charms of them and of all magicians, and the tricks and illusions of jugglers. But as honour and rewards would hinder him from the greatness of his experimental work he scorns them.

Such an ideal was very far, however, from the aspiration of the schoolmen, who paid scant attention to matters with so little bearing on salvation or preferment. The Renaissance humanists, who thought all good things came straight from Greece or Rome, for their part deliberately ignored them. They were in revolt against the whole achievement of the Middle Ages, which they stigmatized as barbarous and Gothic.

Medieval architecture

Yet we, who are no longer fighting a life-and-death struggle against feudalism, have only to look at the development of that Gothic architecture, from the dark massiveness of the Norman to the luminous lightness of the perpendicular, to see that those three centuries span a world in rapid technical advance. Architecture was indeed the greatest and most characteristic expression of medieval technique and thought. It was, however, a purely technical rather than a scientific achievement.

The marvellous construction of vault and buttress, far more daring than anything the Romans or Greeks attempted, were the result of a series of *ad hoc* solutions to practical difficulties. Theory did not enter into them at all; nor could it, for the theory of the arch, apart from the working knowledge of it, was only discovered in our time. For the same reason medieval architecture contributed little, directly or indirectly, to the advance of science. It was different with other innovations, some of which, like the compass or gunpowder, were to furnish the bases of the new science, while others, like horse harness and the sternpost rudder, were to affect science indirectly through the improvement in productivity they brought about.[1.13; 1.14 2.29; 2.30]

Technical innovations from the East and China

The technical advances of the Middle Ages were made possible by the exploitation and development of inventions and discoveries which, taken together, were to give Europeans greater powers of controlling and ultimately of understanding the world than they could get from the classical heritage. Significantly, the major inventions—those of the horse-collar, the clock, the compass, the sternpost rudder, gunpowder, paper, and printing—were not themselves developed in feudal Europe. All seem to have come from the East and most of them ultimately from China.

As we come to know more about the history of science in China (and there Dr Joseph Needham's great study of the origins and history of Chinese techniques and science will be invaluable),[3.4] we are beginning to see the enormous importance for the whole world of Chinese technical developments. Already enough is known to show that the whole concept of the superiority of Western Christian civilization is one based on an arrogant ignorance of the rest of the world. Transmission is always difficult to prove, but the fact remains that many inventions only appearing in the tenth century or later in western Europe were fully described in China in the very first centuries of our era.

What still requires to be explained is why this early technical advance in China, and to a lesser extent in India and Islamic countries, after a promising start came to a dead stop before the fifteenth century, and why it resulted in the formation of Oriental civilizations with a high but static technical level. The reason given by Dr Needham as especially applicable to

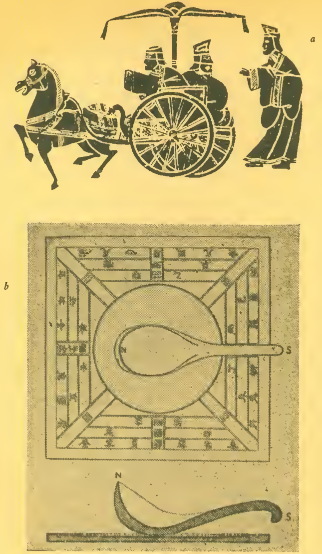


FIG. 7.—TECHNIQUE AND SCIENCE IN EARLY CHINA

(*a*) Rubbing from tomb of Wu Liang, A.D. 147, showing improved horse harness and shafts.
(*b*) Reconstruction by Wang Chen-To of earliest form of compass. The balanced spoon is made of magnetite. The board is a diviner's board of Han times, *c*. A.D. 100.

China is the rise of a bureaucracy—the Mandarins—with a literary education, having no interest in improving technique and being very concerned with keeping down the merchants, who alone could have driven techniques forward by opening up new markets.*

It was precisely this that was to happen in Europe. The new inventions, in the measure in which they came to be used, set in motion a revolution in technique which contributed in a cumulative way to the breakdown of feudal organization through increased productivity and trade. Better means of agricultural production in the villages meant more surplus to exchange. Better transport of bulk goods relieved the need to produce everything from land more suited to a particular crop, and thus indirectly increased productivity. For instance, whole districts round Bordeaux were given up to wine-growing in the thirteenth century, for wine was the first bulk cargo, as witness our present heavy unit of weight, the ton—originally the weight of a tun or a barrel of wine. Trade in turn enhanced the importance of merchants and thus of the towns, and handicraft industry began to grow in town and country.

The characteristic of medieval economy most significant for the future was that the towns did not dominate the country. The feudal system maintained this independence, and the absence of slaves prevented the rise of factories on the classical pattern. The industry which arose from the new inventions was spread over hundreds of villages. This was particularly so when mills became a main source of power not only for grinding corn, but also for a variety of industrial processes from fulling to forging. Mining and smelting had necessarily to be scattered, country industries. This rural location increased the chronic labour shortage already mentioned, and put a premium on mechanical ingenuity. Moreover, by going to the country the restrictions imposed by town guildsmen on new processes which would put them out of work could be evaded.

The new horse harness

Of the inventions listed, the first two, the horse-collar and the mill, were essentially more efficient ways of transmitting power. Of these the first had the most immediate effect; by substituting a collar, pulling on the shoulders of the horse, for a band across his breast, which constricted his windpipe, the permissible tractive effort was increased fivefold.[2.30] This

innovation, coming from seventh-century China, reached Europe early in the eleventh century. Its immediate results were that horses could take the place of oxen at the plough, and in addition acres of land unsuited to ox-ploughing could be cultivated. At the same time the horse-cart took the place of the ox-cart. The simultaneous introduction of nailed horseshoes put the horse on the road for pack and wagon transport. The advantages of the new horse harness accrued in the first place to the countries of the Franks and Normans and began to make the area round the North Sea and the Channel, already favoured by good soil and a drought-free climate, a major centre of production. The surplus of corn, fish, hides, raw wool, and cloth—the main commodities of the new heavy merchandise—could then be exchanged at great fairs, such as those of Champagne, for the more finished but lighter products of the East and the South.

The water-mill and windmill

The actual invention of water-mills belongs to the classical period; one is described by Vitruvius (*c.* 50 B.C.). The mill, however, has a right to be considered as a medieval device because it was only in the Middle Ages that it came to be widely used. Roman mills were few; streams were not very suitable for them, and Mediterranean slaves could always be found to do the work. In contrast, the mill was, from the start, an integral feature of feudal economy. A mill and a miller were to be found in almost every manor (5,000 of them are listed in the Domesday Book) and the lord made full use of his right to demand that all his serfs have their corn ground at his mill.

Nor were mills limited to grinding corn; they opened the way to a more general use of power. Wherever steady or repeated applications of force were necessary to which work could be brought—for the mill was intrinsically static—mill mechanism could be adapted. For the conversion of rotary into reciprocal motion came two devices, both apparently from China, the trip-hammer and the crank;[3,4] the latter is important because, unlike the trip-hammer, it can also be used to convert reciprocal into rotary motion. Windmills, apparently from Persia, reached Europe about 1150. Mills were used for fulling cloth, blowing bellows, forging iron, or sawing wood, but not until the Industrial Revolution (p. 367) for the equally arduous but more scattered tasks of spinning, weaving,

or threshing. The very fact of the use and rapid development in Europe of mills for so many purposes bears witness to the shortage of labour and to the connection between this and technical and scientific development.

Wind and water-mills needed to be made and serviced, a task beyond the skill of most village smiths. So there grew up a trade of *millwrights* who went about the country making and mending mills. These men were the first mechanics in the modern sense of the word. They understood how gears could be made and how they worked as well as the management of dams and sluices, which made them hydraulic as well as mechanical engineers. They were the repositories of ingenuity from which the Renaissance, and even more the Industrial Revolution which followed it (p. 389), drew the craftsmen who alone could have put into practice the ideas of the new philosophy.

The clock and the watch

The mechanics also had a hand in the development in medieval Europe of the present form of mechanical clock. The clock, as its name implies, was originally just the bell (cloche) rung to mark the hours of service—later all the hours. It was rung by a watchman using an hour glass. Somewhere in the eleventh century an ingenious mechanism, the verge and folliot, which imparted a to-and-fro motion to the clapper, was devised. All the watch had to do was to release a weight which, through a train of *clockwork* (essentially a lighter form of millwork), struck the appropriate hour. It occurred to some millwright or monk that the same mechanism working over and over again could be used to tell the time itself, thus making a mechanical *watch*—as it is still known in the trade—and eliminating the watchman. So the mechanical *clock*, which included the watch, was born, the prototype of modern automatic machinery—self-regulating as well as self-moving.

Timepieces are of course of great antiquity. The Arabs improved greatly on the Greek water-cloçks and made them the basis of many complicated and automatic devices; but these were operated by floats and cords and lacked the precision and the force of trains of gear wheels. We now know, however, that cog-wheel gearing has a far greater antiquity both in Greece and China.* The clock can no longer be claimed as a European invention, though it was most developed there. Clocks were

objects of prestige, rather than of use. They were the pride of towns or cathedrals, but the rare trade of clockmaker and afterwards of watchmaker was in the Renaissance to become for science what the millwright was to be for industry—a fruitful source of ingenuity and workmanship.

The mariner's compass

The observation of the directive power of the earth's magnetism on a natural magnet or lodestone must have been one of the most difficult, as well as the most important, of scientific discoveries. There seems little doubt that the directive property of a pivoted lodestone was known to the Chinese several centuries before we have any record of its use elsewhere.

The discovery seems to have been made, according to Dr Needham,[3.26] as a by-product of geomantic divination—a practice of throwing objects on a board and foretelling the future from the way they lay. These practices still continue and have, incidentally, given us most table games, including dice, cards, and chess. One object was the sign of the North, the Great Bear or Dipper, represented in the form of a spoon. Such spoons cut from lodestone—one of the five sacred stones—would always point in one dirction. It was discovered before the sixth century that this pointing property was also possessed by pieces of iron touched by the lodestone or even allowed to cool when pointing north and south. A water compass in which such a piece of iron was supported on wood is fully described in the eleventh century, but was probably known long before. This is the traditional Chinese compass, its association with the divining boards being shown by the symbols on its frame (Fig. 6). How it passed to the West is still a mystery. There is a reference to it as already well known in a twelfth-century saga. The pivoted needle and the card with the windrose seem to be Italian inventions of the thirteenth century.[3.6]

The slow development of the compass after its first discovery bears all the marks of traditional, technical improvement; but science was early invoked to explain its action. The first original scientific work of western Christendom was *Epistola de Magnete* (1269), the work of Peter the Pilgrim (de Mericourt), the contemporary of Roger Bacon, who admired him as the greatest and most practical scientist of the age (p. 229). It shows a great independence of thought and a capacity for planning and carrying

out a sequence of experiments. From this work—after a long interval—were to stem the researches of Norman and Gilbert (pp. 299 f.), from which was to come the whole of the theory and practice of magnetism and electricity. Not only that, but the influence of the magnet on the compass was to provide the real scientific basis of the doctrines of influence and inductions which had previously been purely magical. Even more important, it was to furnish a working model of the doctrine of attractions which permeated the whole of science, and which was to be the guiding star of the great synthesis of Newton.

The sternpost rudder

The sternpost rudder also apparently came from China. The Chinese junk is radically different from the ship in that, while the latter was developed from the original dug-out canoe by building up the sides around a central keel, the former is derived from a bamboo raft by lifting up bow and stern.[2.29; 3.21] It has no keel and the natural place for the rudder is the middle of the stern. In Europe the central rudder was more difficult to attach because of the old sloping form of the keel at the stern, and a steering oar fixed to the *star*board was used, but once this was done by adding the vertical *stern*post somewhere in the thirteenth century, it made the deeper-keeled European vessels, based on Viking models, much better sailers. A course could now be held with sails set closer to the wind. This in turn led to the development of the fore-and-aft sail from the older lateen sail. Winds astern had no longer to be waited for and voyages could be made in rougher weather.

The two navigational inventions, the compass and the sternpost rudder, were to have an effect at sea of importance comparable to that of the horse harness on land. Their use made open sea voyages feasible, and such voyages largely took the place of the roundabout coasting of earlier times. They threw the oceans, for the first time, open to exploration, war, and trade, with enormous and rapid economic and political results.

Navigation

The scientific consequences of the development of navigation were to be of critical importance. Open-sea navigation, even in the Mediterranean, required astronomic observations and charts, and gave a direct stimulus to the development of an

astronomy capable of accurate predictions, of a new quantitative geography, and of instruments suitable for use on shipboard. Ocean navigation further raised the urgent problem of finding the longitude, at which all the great astronomers of the seventeenth century were to try their hand. The need for compasses and other navigating instruments brought into being a new skilled industry, that of the card and dials makers, whose subsequent influence on science, particularly in setting higher and higher standards for accurate measurement, was enormous. Many scientists, including Newton himself, were instrument makers, and one instrument maker, Watt, was to have a revolutionary effect on industry and on science.

Gunpowder and cannon

Of all the inventions introduced to the West in the Middle Ages, it was the most destructive—gunpowder—that was to have the greatest effect politically, economically, and scientifically. The original invention has been claimed for the Arabs and the Byzantine Greeks, but the balance of evidence is for a Chinese origin. The key to its operation is the addition of a nitrate (nitre) to make combustible substances burn without air. Nitre occurs naturally in some salt-pans and also in overmanured ground. Either it was first used by chance, in firework compositions, or possibly it was noticed that using it instead of soda (natron) as a flux with charcoal led to a bright flash and mild explosion. In China for some centuries it was used merely for fireworks and rockets.

The military importance of gunpowder started when it was used in the cannon, perhaps derived from the fire-tube of the Byzantines, but more probably from the bamboo cracker of the Chinese. The very name of the barrel of a cannon indicates its primitive construction from iron staves hooped together. The cannon, and the hand-guns which soon followed them, were effective in war not so much because their range or power exceeded that of the old catapults and ballistæ, but because, for all their clumsiness and cost, they were far cheaper and more mobile. Their use in battle and sieges initiated a technical revolution in warfare, comparable only with that which took place at the beginning of the Iron Age 3,000 years before.

Against foes without it, gunpowder, with cannon and muskets, gave practical invincibility and thus put " civilized " man in a position of effective superiority against far more

numerous "natives." But even among the civilized it enormously altered the balance of power. Once cannon came in they became a necessity for victory, and from an economy turned into a new expense of war. Only wealthy republics or kings backed by merchants could command sources of metal and the technical skill to fashion it into cannon. This fact broke the independence of the land-based aristocracy as surely as their castles were battered down by cannon balls. The triumph of gunpowder was the triumph of the national State and the beginning of the end of feudal order.

At sea the effect of gunpowder was no less important. Used in naval guns, mounted in ships directed by the new astronomy and the compass, gunpowder was to make the western Europeans supreme over the sea-ways of the world from that time to the middle of the present century. It enabled Europeans to stamp their pattern of culture on others, originally by no means inferior, culturally or militarily. More immediately it enabled them to concentrate the accessible wealth of the world in their hands, and so to possess the accumulation of capital which financed the Industrial Revolution.

The scientific consequences of gunpowder—chemical and physical

Ultimately, however, it was the effects of gunpowder on science rather than on warfare that were to have the greatest influence in bringing about the Machine Age. Gunpowder and the cannon not only blew up the medieval world economically and politically; they were major forces in destroying its system of ideas. As Mayow put it, "Nitre has made as much noise in philosophy as it has in war." In the first place they were something new in the world—the Greeks did not have a word for them. In the second place the making of gunpowder, its explosion, the expulsion of the ball from the cannon, and its subsequent flight furnished problems the practical solution of which led to a search for causes of a new kind and the creation of new sciences (Fig. 10, p. 294).

Whatever the origin of gunpowder, the essential ingredient —nitre (potassium nitrate)—could have been produced only as the result of a careful study of the separation and purification of salts, probably in connection with alchemy. Wherever it had to be made it turned attention to the phenomena of solution and crystallization. Moreover, to explain the explosion of gunpowder taxed medieval chemistry and physics to the utmost.

It was clearly an action of fire, but unlike all other terrestrial fires it did not require air. This led to the speculation that the air was provided by the nitre and conversely that air contained nitre, or at least a nitrous spirit (*anima*). It thus became the model for all subsequent attempts to explain combustion and with it breathing, that animal necessity for air. Ultimately, after four centuries of argument and experiment, it was to lead to the discovery of oxygen and with it to the whole of modern chemistry (pp. 445 f.).

The force of the explosion itself, and the expulsion of the ball from the barrel of the cannon, was a powerful indication of the possibility of making practical use of natural forces, particularly of fire, and was the inspiration behind the development of the steam-engine (pp. 414 ff.). Later we shall see how the machinery developed for the boring of cannon (p. 417) was to be used in making accurate cylinders which gave the early steam-engines a chance to prove their efficiency.

Finally, the movement of the cannon ball in the air—ballistics—was to be the inspiration for the new study of dynamics. The classical scientists had studied bodies at rest, or bodies acting on each other with relatively steady forces. The new world was to consider the problem of bodies in violent motion, and on this basis was to found a new and much more comprehensive mechanics. Impetus theory came long before the cannon, but the interest in the flight of shot focused a new attention on it. The new mechanics differed from the classical in one vitally important respect: it depended on, and in turn generated, mathematics—it was quantitative and numerical.

Distillation and alcohol

The first preparation of strong spirits of wine was made in Europe in the twelfth century, although most of the steps leading up to it had already been taken in their development of distillation by the Arabs. The last decisive step was probably made in Salerno, whose medical school was already famous. It had been founded in the ninth century, and eventually absorbed the best of Arab science from that melting-pot of Greek, Arab, and Norman culture—Sicily. As the distillation of perfumes and oils was already known, alcohol was probably hit on by accident in the course of some medicinal preparation. The clue to its preparation was to cool the still-head or alembic sufficiently to condense the alcohol as well as the water.[2.19]

The resulting distillate was first drunk as a rare medicine and its cordial properties were noted. Soon it could be made strong enough to burn, which added much to its prestige. In the fourteenth century, Raymond Lull is alleged to have distilled wine with quicklime and produced nearly absolute alcohol. The name is a misnomer; the Arabic term really applies first to eye-paint and then to any fine powder. The great demand for alcohol—fire water, usquebaugh, whisky, burnt wine, brandy wine—came only with the Black Death in the fourteenth century. It was believed that those who drank it regularly would never die, hence the name *aqua vitæ*. After that it got right out of the control of the doctors and began to be produced in quantity, as attested by the numerous laws promulgated against its use. Alcohol gave rise to the first scientific industry, that of the distillers, the foundation of the modern chemical industry.

The social and scientific results of the preparation of alcohol were manifold. The most obvious, the effects of drinking it and the craving it produces, were of no great social importance in Europe, but in heathen parts alcohol was second only to gunpowder in its civilizing mission. (Manhattan Island was purchased by the Dutch from the Indians in 1626 for three barrels of rum. The name means " the place where we got drunk.") For science, alcohol had a double significance—chemical and physical. The capture of the spirits of alcohol gave great impetus to applying the same method to other substances. Now, the far more efficient, water-cooled condensers that were produced by the industry meant that other volatiles, such as ether, might be condensed. The still and condenser supplemented the alembic and retort as the chief laboratory apparatus and made organic chemistry possible (Fig. 8, p. 263).

The physical processes of distillation, particularly the strange transfer of heat from the fire to the condenser water, proved very difficult to understand. As we shall see (p. 416), it was left for Black in the eighteenth century to draw from it the doctrine of latent heat—which was the beginning of thermodynamics. In turn it was from this doctrine that Black's instrument maker, Watt, invented the separate condenser and produced the first thermally efficient engine.

Lenses and spectacles

The discovery of lenses already described (p. 202), led by 1350 to the invention of spectacles, apparently in Italy. Their

use gave still further impetus to the study of optics. Grosseteste, Roger Bacon, and Dietrich of Freiburg made contributions to science in explaining the action of the lens both in focusing light-rays and in magnification.[3.16] What is perhaps even more important, the demand for spectacles gave rise to the trades of the lens grinders and spectacle-makers. It is to one of them, traditionally Lippershey in 1608, that we owe the invention of the telescope, and it would seem, at least at that stage, that the casual combination of lenses, possible only in a spectacle-maker's shop, was more fruitful than any theoretical conjectures on the magnification of images.

Paper

The last two technical introductions from the East, which were fated to have a far greater effect in the West than in their land of origin, were the linked inventions of paper and printing. The need for a writing material cheaper than the very expensive parchment, became more and more urgent with the spread of literacy. The process of paper-making was developed originally in China, based on vegetable fibres. It was already being used there as a cheap writing material in the first century B.C. It was introduced to Europe via the Arabs in the twelfth century. In Europe linen rags provided the basis for the first paper of quality, since then unexcelled. Paper turned out to be so good and cheap that its increased availability led in turn to a shortage of copyists and hence to the success of the new method of copying which printing provided.

Printing

The technique of printing is not a very difficult one to invent or to practise. In fact in seals, rubbings, and stampings it has been used since the very earliest times. Its rapid spread in Europe was an example of a social and organizational need making use of and further developing a technical device. Before a need can be effective it must be felt to exist. But the particular need that brings the technique into existence is not necessarily the main one that the new technique ultimately comes to serve.

Even in the late Middle Ages few people were aware of the need for a large quantity of paper books. In fact, printing would probably not have been developed in the first place merely for literary purposes. The full value of printing is felt

only when large numbers of cheap copies of one text are needed. Consequently it is not surprising that it first arose in the East for the reproduction of Taoist or Buddhist prayers, where quantity is a definite spiritual advantage, and later for the printing of paper money, which also implies large numbers. In the West, oddly enough, it was another use, the development of playing-cards, originally a form of divinatory magic, that gave rise to the need for large-scale block printing, with papal indulgences, prayers, and sacred images not far behind.

Cheap books, religion, and the new learning

Printing with movable wooden type was originally a Chinese invention of the eleventh century. Movable metal types were first used by the Koreans in the fourteenth century. It was introduced into Europe in the mid-fifteenth century and spread extraordinarily rapidly, first for prayers and then for books. The new, cheap, printed books promoted reading and thus created the need for more books, so setting off a kind of explosive or chain reaction. Naturally the printers first concentrated on producing larger numbers of the books that had been most in demand as manuscripts. The original centre of interest was in religion and particularly in the Bible, whose printing and dissemination to the rising middle classes fell in with the new trend of emancipation of thought from Church control that was to lead to the Reformation. A close second was literature and poetry, both ancient and modern, for the delight of the now cultured aristocracy and upper bourgeoisie of the Renaissance.

Later still, largely in the sixteenth century, printing was to be the medium for great technical and scientific changes by its setting out at large, for all to read and see, descriptions of the world of Nature, particularly of its newly discovered regions, and also, for the first time, of the processes of the arts and trades. Hitherto the techniques of the craftsmen had been traditional and never written down. They were passed on from master to apprentice by direct experience. Printed books made it first possible and then necessary for craftsmen to be literate. Their descriptions of technical processes, and even more their illustrations, helped to bring about for the first time close relations between the trades, the arts, and the learned professions (p. 264).

6.7—*THE DEVELOPMENT OF LATE MEDIEVAL ECONOMY*

This discussion of the importance of printing has brought us beyond the limits of the Middle Ages but, before passing to a consideration of the revolution in science of the Renaissance, it is necessary to assess the effect of these and other technical advances taken together on the economy and ideas of the late Middle Ages. Over the countryside as a whole the combined effects of improved production and transport were to increase the gross surplus of the village and consequently the amount of manufactures that could be consumed there.

All over Europe, though the dominance of feudal lords was not yet shaken, wealthy peasants and urban workers strengthened their position and began to provide a large-scale market. This in turn stimulated the manufacture of goods, particularly of semi-luxuries like wine and good cloth (rough cloth was still spun and woven at home), and the production of extra food, like salt fish, and also of metals, particularly iron for tools and weapons. These manufactures, though carried on more often in the country as a part-time peasant occupation, were dominated by town merchants. By the mid-thirteenth century, which may be thought of as the turning point of the Middle Ages, the rich town merchants had acquired through their dominance of the guilds a monopoly position which they used in order to buy cheap and sell dear.

These town oligarchies were often in violent opposition to each other, sometimes to the extent of war. Towards the latter part of the Middle Ages they began to appreciate the value of co-operation for the common exploitation of less developed territories. The most famous of these associations was the North German Hanse, centred on the exploitation of the Baltic trade. From about 1358 to 1550 it virtually ruled the old Viking strongholds of Scandinavia. The Hanse had its own navy and maintained factories in other towns, from the Steelyard in London to Novgorod, with extra-territorial rights. By concentrating on buying up raw materials in outlying countries and selling them as finished goods, it depressed the development of industry outside its own cities.

This extension of the range of action of city leagues postponed but did not remove the causes of conflict inside the

cities. Nor was it possible for foreign merchants to maintain commercial domination indefinitely in the face of the growth of native resources. Britain, for instance, was, up to the fifteenth century, a country exporting raw wool which was worked up in Flanders and Italy.[3.32a] Financially it was dominated by Lombards, Florentines, and Hansards. It had become, in fact, a semi-colonial country though, like the North American colonies in the eighteenth century, one with such resources that its economic independence was only to be a matter of time. Indeed its emancipation started with the development of the domestic weaving of wool as early as the fourteenth century.

In the most advanced medieval cities, those of Italy and the Low Countries, the rule of the wealthy guildsmen provoked revolts of the craftsmen, like that of the Ciompi in Florence in 1378 and of the weavers of Bruges, Liége, and Ghent from 1302 to 1382. Though these revolts succeeded, they did not lead to the achievement of city democracies of the Greek type, because the medieval cities were set in a far more developed and populous feudal countryside. Instead, the final result of struggles inside or between cities was to strengthen either the feudal kings or the merchant princes and hired captains (*condottieri*), who seized power in Italy. This was to lead to the establishment of the nation States of the Renaissance, still feudal in essence but centred on the towns. It was only in a later period that the capitalist system was to grow from this bourgeois nucleus.

Commerce and mathematics

It is to the cities, therefore, that we must look for the development of ideas and particularly of science in the later Middle Ages. Here were growing up a new lay intelligentsia, good Christians but largely independent of, and in some degree in opposition to, the Church, which was still by far the greatest landowner, and firmly attached to the feudal system. At first, however, their interests hardly clashed, for the new *bourgeoisie* were interested more in profit and display than belief. Commercial arithmetic, fine craftsmanship, and art concerned them far more than the disputes of the schools. It was only later, when they found the Church an obstacle to their increasing wealth and power, that they were to become the most ardent advocates of reform.

The Arabic numbers introduced by Leonardo Fibonacci

in 1202 found their main use in commercial accountancy. Within a few decades the four rules of arithmetic, hitherto a mystery confined to a handful of mathematicians, became a necessary training for every merchant apprentice, incidentally creating a large body of persons able to appreciate mathematics. The result was symbolic algebra and the signs of $+$ and $-$, originally checkers' marks for over and below weight. It was the same mercantile interest that first kept up and later improved astronomical tables and new maps for the benefit of navigation.

Art and science

The increased wealth of the merchants gave a new impulse to art and at the same time changed its objects and its style. Though still expressed in a religious form, it was no longer the Church art of the early medieval period as embodied in the Gothic cathedrals. Illustrations from Nature took the place of theological symbolism. Art was becoming at the same time more secular and more naturalistic. Much of the surplus accumulated by the merchants was spent on mansions and pictures, partly for pleasure, partly for prestige.[1.32] The number of craftsmen multiplied, and their techniques were continuously improved. In textiles, pottery, glass, and metal-work there was ample incentive and opportunity for practical research in the properties of matter, physical and chemical. This was to provide the material basis for the revival of science. The stage was set for the full flourishing of the Renaissance.

6.8—*THE ACHIEVEMENT OF THE MIDDLE AGES*

The legacy of the Middle Ages was essentially economic, technical, and political. Its intellectual contribution was not so lasting. For whereas the foundation laid by feudal economy modified by urban trade was able to support the further advances of the Renaissance and the Industrial Revolution without any breakdown, the ideas of the Middle Ages had to be ruthlessly scrapped before a new scientific philosophy could take their place. This is not to disparage the enormous intellectual effort of the scholars of the Middle Ages involved in recovering and absorbing the elements of classical science. However, for the reasons already discussed, they were as

incapable as the Arabs before them of advancing beyond the limits that had been reached by Aristotle nearly 2,000 years earlier.

The medieval contributions were certainly more finished than those of the Arabs. They had established the principles of the scientific method. Robert Grosseteste at the outset of the period had stated the double method of *resolution* and *composition* or of *induction* and *deduction* as clearly as Newton was to put it 500 years later.[3.16] But method without either the desire or the means to use it is almost worse than useless. The complacency it generates is in itself a bar to advance.

The fundamental reason why that advance was so long delayed was that in a feudal economy, Islamic or Christian, there was no way in which rational science could be used to any practical advantage. Astrology was esteemed enough by princes to keep astronomy going, and alchemy may have improved chemical technique, but owed little to reason, its theories being almost pure magic. As long as science was called on mainly to provide examples for theologians there was no reason to demand more than a formal analogy to experience. The searching test of practical use need never be applied. Science through the Middle Ages was accordingly largely confined to book learning and disputation. The intellectual advances that were to come later owed little to the schoolmen except the stimulus provided by the desire to prove them wrong. They were to come rather from the combination of the rediscovery of the best of classical thought with the new

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TABLE 3.—*Science and Feudalism : Salvaging the Hellenic Legacy*

(*Chapters 5 and 6*)

This table covers the 900 years from 500 to 1400. Throughout, the content of scientific thought—it would be hardly accurate to call it advance—is essentially Hellenic and indeed marks a direct continuation of that covered in Table 2. In contrast, the areas in which science was studied were far more widely scattered and the centres of interest in science varied with the time. Alexandria, Syria, Persia, Central Asia, India, China, were all active in the first part of the period. Spain, Italy, France, England, and the Low Countries in the latter part. It can be seen that, apart from a small burst of activity under Justinian, the three other significant but not major bursts occurred in Islamic Asia in the ninth century, in Islamic Spain in the eleventh, and in France in the thirteenth century. It is difficult to assign precise dates to the technical developments that were to be decisive in the next phase, such as the compass and gunpowder. All that can usually be indicated is the approximate date of introduction into Europe.

Table 3

Period	Date	Technical Developments	Political and Social Events	Philosophy and Science	
The Transition to Feudalism (Chap. 5)	500				
		St Sophia built	*Justinian* closes the Academy of Athens	*Dionysius* mystical theology	*Aryabhata*, *Varahamihira* — Indian astronomers and mathematicians
		Silk introduced into Europe from China	Persian university of Jundishapur	*Philoponos* anti-Aristotelian doctrine of impetus	Development of decimal numeration, the zero
	600				
			T'ang dynasty in China		
		Block printing in China	*Mohammed's* mission, spread of Islam to Persia, Africa, and Spain		*Brahmagupta* algebra and trigonometry
				Severus Sebockt introduction of Hindu numerals into Syria	
	700				
		Use of wheeled plough and three-field system in Northern Europe		Translations from Greek into Syriac *Geber* legendary founder of Islamic chemistry	
			Abbasid caliphs Baghdad founded	Translations from Sanskrit, Syriac, and Greek into Arabic	
	800				
		Vikings improve sailing-ships	*Charlemagne* *Haroun-al-Raschid*	House of Learning	
		Introduction of horse-collar, shoes, and stirrups into Europe from China	Europe invaded by Northmen and Magyars	*Al-Kindi* first Arab philosopher *Erigena* first philosopher Rise of Sufism, neoplatonist alchemical mysticism	*Al-Khwarizmi* algebra *Bede* first historian of Christianity
	900				
		Widespread use of water-mills	Break-up of caliphate	*Alfraganus* founder of Islamic astronomy *Rhazes* medicine and chemistry *Abul Wafa* trigonometry	*Al-Masudi* geometry
The Middle Ages (Chap. 6)	1000	Windmills in Persia	Reform of Church		
			Struggle of Pope and Emperor	*Avicenna* medicine and physics	*Al-Biruni* description of India
		Use of lenses		*Alhazen* founder of optics	
			Rise of Italian cities	*Arzachel* Toletan tables, elliptic orbits	
		Alcohol	Invasion of Seljuk Turks	*Al-Ghazzali* return to mysticism	*Omar Khayyam* mathematics
	1100	Paper in Spain	First Crusade		
		Stained glass	Communes in Flanders	*Peter Abelard* University of Paris, beginning of scholasticism	
		Windmills in France		*Averroes* Aristotelian Islamic system	
		Mariner's Compass	*Saladin* retakes Jerusalem	*Maimonides* Aristotelian Jewish system	
	1200				
		Gunpowder introduced *Villard de Honnecourt* mechanical contrivances and clocks	*Frederick II* Emperor	Translations from Arabic into Latin. *Leonard of Pisa* introduction of Arabic numbers *Robert Grosseteste* science in support of faith	
			Mongols sack Baghdad	*Roger Bacon*, *Peter the Pilgrim* experiment and science for use *St Albert*, *St Thomas Aquinas* Aristotelian Christian System	
	1300				
		Use of spectacles	Schism in papacy	Al-Tusi Ilkhanic Table	*Raymond Lull* Sufic mysticism and alchemy
		Cannons used in war Sternpost ships Oil painting	Hundred Years' War Black Death Peasant revolts	*Duns Scotus*, *William of Occam* nominalism Decay of scholasticism *Buridan*, *Oresme* development of impetus doctrine	
	1400				
			End of schism	*Ibn Khaldun* science of history	*Ulugh Beg* Samarkand observatory
		Printing	Hussite revolt	*Nicholas of Cusa* speculation on the earth's movement	
	1450				

experimental methods inspired by a new practical interest in the world of Nature and art.

Much more significant for the future than medieval thought was the impressive total of technical development in manufacture and transport, and the legacy of difficult practical problems requiring the application of intelligence for their solution. The question raised at the outset as to what determined the time and place of the birth of modern science (p. 32) can be partly answered in terms of these considerations. Of the heirs to the first great burst of Hellenistic natural science, only western Europe was in a shape to make any forward move. By the fifteenth century the Islamic world had collapsed economically and had been ruined by internecine war and invasion. For all the later successes of the Turks and Moguls it had lost its intellectual drive. Its religion had ceased to be liberal and shrank to a narrow orthodoxy. India had become a battleground between waves of Islamic invaders

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MAP 3.—MEDIEVAL EUROPE

This map illustrates the distribution of towns and centres of learning in Medieval Christendom discussed in Chapter 6. It brings out the concentration on the central spine of Europe (pp. 209 f.) and the two major trade routes of the Rhône and the Rhine running on each side of the Alpine barrier. Four areas are specially indicated as centres of economic revival: the North Sea area (N); the two Italian areas of Lombardy (L) and Tuscany (T); and the West Mediterranean area of Provence and Languedoc (P) which might be stretched to include Barcelona and the Balearic Islands. The embryonic industrial areas also marked are the copper and silver mines of Saxony (1), the tin mines of Cornwall (2), the iron mines of Styria (3), and the coalfields of Newcastle (4) and Belgium (5).

Aa—Aachen
Ab—Aberdeen
Ax—Aix
Al—Albi
A—Amsterdam
Au—Angers
Aw—Antwerp
Au—Augsburg
Av—Avignon

Bl—Barcelona
Ba—Basle
B—Berlin
Bg—Bologna
Bo—Bordeaux
Br—Bristol
Bu—Bruges
Bs—Brussels
Bd—Buda

Ca—Caen
Cl—Calais
Cm—Cambrai
Cb—Cambridge
Co—Cologne
Cu—Constance
Cp—Copenhagen

Di—Dijon
Dr—Dresden
Du—Dublin

E—Edinburgh

F—Florence
Fr—Frankfort

Gv—Geneva
Ge—Genoa
G—Ghent
Gl—Glasgow

H—Hamburg

I—Innsbruck

Ld—Leyden
Li—Liège
Lm—Limoges
Ln—Lincoln
L—London
Lu—Lübeck
Ly—Lyons

Ma—Magdeburg
Mz—Mainz
Ms—Marseilles
M—Milan
Mp—Montpellier
Mu—Munich
Mt—Münster

Na—Namur
Np—Naples
Nw—Newcastle
No—Norwich
Nb—Nürnberg

Or—Orleans
O—Oxford

Pl—Palermo
Pm—Palma
P—Paris
Pi—Pisa
Pt—Poitiers
Pr—Prague

Ra—Ravenna
Rh—Rheims

R—Rome
Rn—Rouen

Sa—St Andrews
Sl—Salerno
Su—Salonika
Si—Sienna
St—Strasbourg

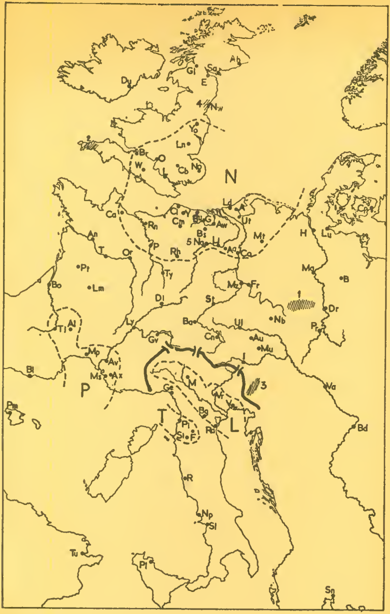
Tl—Toulouse
T—Tours
Ty—Troyes
Tu—Tunis

Ul—Ulm
Ut—Utrecht

V—Venice
Vr—Verona
Va—Vienna

W—Winchester

Y—Ypres
Yo—York



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and a Hinduism frozen in a caste structure that provided stability at the expense of any possibility of advance. China preserved its old culture, but with a State system that prevented it, and would prevent it for another 400 years, from taking the necessary step of linking technique and book learning.

Culture in Europe at the end of the Middle Ages was hardly materially or even intellectually at a higher level than in the great empires of Asia. That it held greater promise could only be apparent from its relative lack of fixity and uniformity in social and economic forms (pp. 828 f.). Great as was the weight of tradition, it was being everywhere challenged by consequences of the conflicts between the various interests of town and country, Church and State. Nor was the authority of pope and emperor, themselves most often at cross purposes, sufficient to impose any rigid limit on change. The feudal system itself, that had given its essential character to the Middle Ages, was evidently breaking up by the end of the fourteenth century. But this was not an evidence of social decay, for economically and technically there was in many places indubitable evidence of advance. If an old society was dying a new one was taking its place, one able to make far greater use of the advantages of the natural resources of Europe and the labour of its peoples than had the lords and prelates of the Middle Ages.

PART IV

THE BIRTH OF MODERN SCIENCE

INTRODUCTION

THE development of towns, trade, and industry that was gaining momentum towards the end of the Middle Ages was to prove incompatible with the economy of feudalism. These changes slowly maturing under the surface of the feudal order finally found expression, and in one place after another inaugurated a new order in economy and science. With better techniques, better modes of transport, and more ample markets, the production of commodities for sale steadily increased. The towns where these markets were found had long played a subsidiary, almost parasitic, role in feudal economy; but by the fifteenth century the burghers or bourgeoisie had grown so strong that they were beginning to transform that economy into one in which money payments and not forced services determined the form of production. The triumph of the bourgeoisie, and of the capitalist system of economy which they evolved, took place only after the most severe political, religious, and intellectual struggles. Naturally the process of transformation was slow and uneven; it had begun already in the thirteenth century in Italy, yet it was not until the mid-seventeenth century that the bourgeoisie had established their rule even in the most progressive countries of Britain and Holland. Another hundred years were to elapse before the same class had come to control the whole of Europe.

The same period—1450–1690—that saw the development of capitalism as the leading method of production also witnessed that of experiment and calculation as the new method of natural science. The transformation was a complex one; changes in techniques led to science, and science in turn was to lead to new and more rapid changes in technique. This

combined technical, economic, and scientific revolution is a unique social phenomenon. Its ultimate importance is even greater than that of the discovery of agriculture, which had made civilization itself possible, because through science it contained in itself the possibilities of indefinite advance.

The problem of the origin of modern science is at last being recognized as one of the major problems of all history. Professor Butterfield [3.1] claims for instance that "the so-called scientific revolution . . . outshines everything since the rise of Christianity and reduces the Renaissance and Reformation to the rank of mere episodes, mere internal displacements within the system of medieval Christendom. . . . There can hardly be a field in which it is of greater moment for us to see . . . the precise operations that underlay a particular historical transition, a particular chapter of intellectual development." While I disagree profoundly with the analyses he gives, I fully concede the importance of the problem.

The movements of capitalism and science are related, though much too intimately for that relationship to be expressed in simple terms of cause and effect. It can, however, be said that at the beginning of the period the economic factor was dominant. It was the conditions of the rise of capitalism that made that of experimental science possible and necessary. Towards the end of the period the reverse effect was beginning to be felt. The practical successes of science were already contributing to the next great technical advance—the Industrial Revolution. Thus it was in this period that natural science passed its critical point, ensuring its permanent place as part of the productive forces of society. In the longer view of history this fact is far more important than the political or economic events of the time; for capitalism represents but a temporary stage in the economic evolution of society, while science is a permanent acquisition of humanity. If capitalism first made science possible, science in its turn was to make capitalism unnecessary.

In its early stages, however, when capitalism was breaking the bonds of a decaying feudalism, it was vigorous and expansive. The use of the technical devices of the late Middle Ages enabled agriculture, manufacture, and trade to increase and spread over ever larger areas. The material needs of the economic advance led to further developments of techniques, particularly those of mining, warfare, and navigation. These, in turn, led to new problems arising out of the behaviour of new

materials and processes, which put a strain on the science of classical times in which such inventions as the compass and gunpowder had had no place. The voyages of discovery showed how limited were the experiences of the Ancients, and strengthened the need to find a new philosophy that could see farther and do more.

By the beginning of the seventeenth century a new and enterprising bourgeoisie was able to respond to this stimulus and build up the essentials of experimental science. The new scientists came to be organized, as the merchant adventurers had been, into companies. Before the century was over a small group of able men had been successful in solving the central problems of *mechanics* and *astronomy*. They thus provided more than the science of the Ancients had ever done—practical help where it was needed: in *navigation*. But this was only a slight foretaste; their real triumph lay in the fresh impetus to the scientific study of technique and of Nature, and to the elaboration of the new *experimental* and *mathematical* methods of analysing and solving them, which were to produce their full *fruits* in later centuries. Up to the end of the seventeenth century science had far more to *gain* from its renewed contacts with practical work than it had to *give* in the way of radical improvements in technique.

The scientific revolution

The tracing of the development of the new science from the critical period of its birth and early growth to intellectual maturity is the major task of Chapter 7. It is necessary first to show its relation to the new social forces of the Renaissance and Reformation and then to examine how its achievements were to determine the technology and mould the ideas of the Modern age that was to follow. The change in ideas in science in this crucial period was indeed far greater than that in politics and religion, all-important as these seemed at the time. It amounted to a *Scientific Revolution*, in which the whole edifice of intellectual assumptions inherited from the Greeks and canonized by Islamic and Christian theologians alike was overthrown and a radically new system put in its place. A new quantitative, atomic, infinitely extended, and secular world-picture took the place of the old, quantitative, continuous, limited, and religious world-picture which the Muslim and Christian schoolmen had inherited from the Greeks. The

hierarchical universe of Aristotle gave way before the world machine of Newton. During the transition destructive criticism and constructive synthesis came so close together that it is impossible to draw a line between them.

This substitution was only a symptom of a new orientation towards knowledge. It was changed from being a means of reconciliation of man with the world as it is, was, and ever will be, come doomsday, to one of controlling Nature through the knowledge of its eternal laws. This new attitude was itself a product of the new concern with material wealth and brought about a renewal of interest of the learned in the practice of the trades of the artisan. In this way the Renaissance healed, though only partly, the breach between aristocratic theory and plebeian practice which had been opened with the beginning of class society in early civilization and which had limited the great intellectual capacity of the Greeks.

To understand adequately how modern science began it is necessary to consider both the practical and intellectual aspects of the transformation started in the Renaissance. Writers on the history of science have usually stressed only the latter, and have thus seen the whole transformation either as one from bad to good arguments from self-evident first premises, or as a matter of more careful observation and more correct evaluation of evident facts. That both these explanations are inadequate is shown by their failure to account for the coincidences of the times and places of economic, technical, and scientific advance, and further by the coincidence of subjects of interest to science with those of technical concerns to the controlling groups of society.

On the other hand it is also inadequate to consider only these technical interests. Mental attitudes as well as material concerns must be taken into account. The ideological aspects of the struggle of the emerging bourgeoisie impressed themselves on the scientific as well as the religious ideas of these centuries of transition. Indeed, the challenge to ideas that had been accepted for many centuries could only have been made at a time when the whole foundations of society were in question.

Unlike the previous transitions, where, as at the end of the Roman Empire, a new science was built up on the ruins of the old, or where, as at the beginning of the Middle Ages, science was translated from one culture to another, the revolution which gave rise to modern science occurred without any such break in continuity or outside influence. This emphasizes still

further the fact that a radically new system of thought was being built up in the new society from elements derived directly from the old, but transformed by the thoughts and actions of the men who were making the revolution. The old feudal culture had been tried and found wanting; it could not survive the conflicts that it had itself engendered. The new bourgeois class which it had thrown up had to find their own new social system and evolve their own new system of ideas. The men of the Renaissance and of the seventeenth century certainly felt they were making a break with the past, however much they might unconsciously owe to it.

In one significant respect the Scientific Revolution differed from earlier changes in that it was made easier, especially at the outset, by the consciousness that it was a return to the ideas of an older, grander, and more philosophical culture. The authority of the ancients could be and was used by such real innovators as Copernicus and Harvey (pp. 278 f., 301 f.) to give them a support, not less important than the evidence of the senses. It was a matter not so much of rejecting all authority as of buttressing one against another. The humanist was free to choose, and he could do so for intrinsic reasons. The recovery of at least part of the best mathematical work of classical antiquity, notably that of Apollonius and Archimedes, helped to break the monopoly of Aristotle. Even Plato as a mathematician rather than as a theologian could be a source of inspiration. In a sense, and indeed the best sense, the new science came direct from the Ancients; for it was by following their methods that the men of the new age were able to overthrow their ideas and surpass their achievements.

Major phases in the transformation of science

In order to understand the actual process of the creation of the new science it is convenient to divide the whole period of the Scientific Revolution into three phases which may for convenience be called: those of the Renaissance, 1440–1540; of the Wars of Religion, 1540–1650; and of the Restoration, 1650–90. It must be kept in mind that these are not three contrasting eras but three phases of a single process of transformation from the feudal to the capitalist economy.

In the political sphere the first phase (7.1–7.3) includes the Renaissance, the great navigations, and the Reformation, as

well as the wars which ended political freedom in Italy and led to the emergence of Spain as the first great world power.

In the second phase (7.4–7.6) the results of the opening up of America and the East to European trade and piracy began to be felt in a price crisis which shook the whole economy of Europe. It was the age of inconclusive wars of religion in France and Germany. Far more important ultimately for history were the establishment of the Dutch bourgeois Republic at the beginning of the period and of the British bourgeois Commonwealth at its end.

The third phase (7.7–7.9) was one of political compromise. Though governments were monarchical, the big bourgeoisie held the threads of power in all those countries that were progressing economically. The Dutch set the tone of the period, despite the pomp of the Grand Monarque at Versailles. In Britain this phase marked the beginnings of constitutional monarchy and of rapid commercial and industrial development.

The corresponding developments in science were in the first phase a challenge to the whole world-picture which the Middle Ages had adopted from classical times. That challenge found its decisive expression in the rejection by Copernicus of the earth-centred cosmos of Aristotle, and its replacement by a solar system viewed from a turning earth, a planet like the others.

In the second phase the challenge was made good against heavy opposition by Kepler and Galileo and further extended to the human body by Harvey. This was achieved through the use of the new experimental methods, while the first prophets of a new age in science appeared in Bacon and Descartes.

The third phase marked the triumph of the new science, its rapid growth with its spread to new fields, and its first organization into societies. It is the age of Boyle, Hooke, and Huygens, of a new mathematical–mechanical philosophy. The work of many hands and minds ended in Newton's formulation of the *Mathematical Principles of Natural Philosophy*, a foundation on which it was felt that the rest of science could confidently be built. Final ends gave way to mechanical causes, and the hierarchical universe of the Middle Ages was superseded and replaced by another. From now on, independent particles could interact freely, guided by the invisible constitution of Natural Laws. In turn the knowledge of these laws was seen to be the key to the harnessing of the powers of Nature in the service of man. Sublime contemplation had given way to profitable action.

Chapter 7
THE SCIENTIFIC REVOLUTION

7.1—*THE FIRST PHASE: THE RENAISSANCE 1440–1540*

THE first phase of the transition from feudalism to capitalism is the period which covers the movements of the Renaissance and the Reformation, though these, with their antecedents and effects, extend over a longer period. The economic pattern of commodity production for a market dominated by money payments had existed in scattered cities since the twelfth century. It first became the prevailing form of economy in the fifteenth century along the strip of country reaching from Italy, through High Germany and the Rhineland, to the Low Countries. Of this area it was only in Italy that the greater cities like Venice, Genoa, Florence, and Milan became politically, as well as economically, independent and were able to build up the brilliant artistic and intellectual civilization of the Renaissance. In Italy this implied no break with the Church, for the Holy See in Rome made a handsome income from the contributions of all Christendom. It was otherwise when the movement spread to Germany and farther. There it led on the one hand to the assertion of independence of religion on a national basis, expressed in the Lutheran Reformation, and on the other to fierce social strife which found expression in the Peasants' War of 1525–26 and the revolt of the Anabaptists of Münster in 1533. Similar revolts occurred in Hungary and even in Catholic Spain. Later, when the Reformation spread farther, to the Low Countries, Britain, and France, it was in the still more radical form of Calvinism, rejecting the whole hierarchical Church government and vesting civil as well as ecclesiastical power in the democracy of the elect.

The issue of democracy was, however, not to be raised effectively until the next phase. The political form that was at first to replace the feudal system of graded powers and loyalties was to be the absolute prince, relying for his power on the support of the merchants, and who might even be an ennobled merchant himself, like the Medici. The restoration of monarchy marked an end of the temporal powers of emperor and

pope, and with it the whole scheme of the medieval universe. Instead, nation States began to emerge, with ever-shifting alliances and wars between them, resulting in a precarious *balance of power* in which no one could be supreme.

The courts of these kings or princes provided the patronage for the new humanists and scientists, now no longer dependent on the Church. Indeed the position of the intellectuals became very similar to what it had been in the days of the Arabs, when the learned were also the ornaments of princes. The old medieval universities remained, outside Italy, the stronghold of feudal ideas and opposed the new learning. King Francis I of France was obliged in 1530 to found the Collège Royal, now the Collège de France, to provide for the teaching of the humanities which the Sorbonne would not tolerate.

The Renaissance and the Reformation are two aspects of the same movement to change the system of social relations from that based on a fixed hereditary status to one based on buying and selling commodities and labour. The major economic factor that provided the drive for the movement was the rapid extension of trade made possible by a greater available surplus. This surplus was due to the effect of the technical improvements introduced in the latter Middle Ages, particularly those in agriculture and cloth-making.* At the same time the availability of the surplus was enormously increased by improvements in shipping and navigation. Throughout the fifteenth century the main current of trade, still largely of luxury goods, flowed from the East through Venice into Germany to make the fortunes of Augsburg and Nürnberg, and then to the Low Countries and Britain. It was this trade indeed that gave those areas the leading position in wealth and culture.

However, at the end of the century, at the very culminating point of the Renaissance, there was a critical break-through in the old trade pattern, and one in which science played a decisive part. The development of navigation was to short-circuit the old expensive land-based routes to established markets and to open cheap routes to unimagined new markets. The most spectacular result was the discovery of the New World of America, but more immediately important were the Portuguese capture of the Asiatic sea trade and the rapid development of the Baltic lands and Russia. These shifts of trade routes were to alter the whole economic balance of Europe. The trade of Italy and High Germany was cut off at the roots and their

political and economic importance was to decline, though their cultural and technical influence was to continue for some time longer. Into their place were to come the maritime countries, first Portugal and Spain, and then for a longer period, because they possessed more basic resources, Holland and Britain.

The profits from overseas trade made possible the first accumulation of fluid capital, that is of capital invested in productive enterprise and not only in land. The greed for more profit led to a rapid development of shipbuilding and navigation, of which the latter was to have a decisive effect on the birth of modern science. With paid soldiers instead of feudal levies, wars could be maintained for longer, but they cost more, hence a demand for bronze and iron, for silver and gold. Mining and metal-working boomed, so did the manufacture of gunpowder and the distillation of strong spirits.

The period as a whole was one of economic expansion. In almost every part of Europe production, not only industrial but also agricultural, increased. There was more grain, more cattle, and more fish. It is difficult to attribute this to any specific technical advance; rather was it the result of the accumulation of innumerable separate improvements, together with a more rapid dissemination of improvements through the new channels of trade. The only radical and important technical advance was the introduction of printing, already discussed for convenience in the preceding chapter (p. 241). Though this, in itself, was not a method of production, it was one of the most effective ways of disseminating technical advances, as the number of early printed books on such subjects as agriculture, gardening, cooking, and the trades bears witness.

The humanist revolution in attitudes and ideas

If the Renaissance had only marked a gradual or even rapid improvement of economic conditions it would not occupy the place it does in world history. What gives it its importance in science, art, and politics is that it was a conscious movement, and a revolutionary movement at that. In its intellectual aspect it was the work of a small and conscious minority of scholars and artists. They had set themselves in opposition to the whole pattern of medieval life, and they strove to create a new pattern as near as possible to that of classical antiquity. They no longer wished to see the Ancients through the long chain of tradition, through the Arabs and the schoolmen, but

directly, by digging up the statues, by reading the texts for themselves. This meant going back to the original Greek and encountering at first hand the thought not only of Plato and Aristotle but also of Democritus and Archimedes.

The *humanistic* movement had indeed started in Italy as early as the fourteenth century with Petrarch and Boccaccio. What they appreciated in the classics was beauty of expression and nobility of sentiment, rather than subtleties of logic. In so far as they were philosophical they were Platonist. The humanist movement was to spread to France and northern Europe in the sixteenth century, taking on a more religious flavour. Everywhere it implied a rejection of the specifically feudal ideas of hierarchy and a more secular attitude to society. This did not imply a rejection of religion or even of mysticism, but rather a change of emphasis towards a more personal religion for which the ministrations of the Church were less needed. The cult of the individual, of virtue, in the old Roman sense of manly independence, became the ideal.[4.27]

In Protestant countries the right of private judgment or of special election was proclaimed. Here the humanists, by recovering Greek and Hebrew texts and translating them directly into the vernaculars, were to bring an added weight to the authority of the Bible. Reliance on the literal word of God was to replace deference to the pronouncements of the successors of St Peter. All this fitted an ethical system of a merchant class rejecting the subordination of feudalism. The feudal past was indeed violently repudiated, and with it the architecture which they—the humanists—called Gothic in derision, the philosophy of the schoolmen, the contemplative lives of the monks, the begging of the friars.[4.82] In the end even the Catholic Church itself was forced to reform and accept a break with its medieval past almost as great as that which the Reformers demanded. The doctrine of grace was the Roman equivalent to salvation by faith. The Papacy, which for a century had been in the hands of tolerant humanists, of doubtful morality but great patrons of the arts, was to become almost as rigid as and more intolerant than the most severe Protestant sectary.

Pleasure, art, and money

In Catholic and Protestant lands alike the Renaissance marked a definite and deliberate break with the past. Much

of it was inevitably retained, but a new direction was taken and the medieval forms of economy, of building, of art and thought were to vanish for ever, and to be replaced by a new culture, capitalist in its economy, classical in its art and literature, scientific in its approach to Nature.

The Renaissance was a disturbed but hopeful period compared with the despair of the late classical age and the resignation of the ages of faith that followed. There was less concern with the future life and more with the life of the present, a concern which expressed itself in a rapid growth of secular arts, of painting, poetry, and music. In every form of expression there was a new and frank admission of physical enjoyment. The great prophet of this period, Dr François Rabelais (*c.* 1490–*c.* 1553), chose as the motto for his Abbey of Thelema, the ideal community: "Do what you like" (p. 720) [4.82] Ideally, people lived freely and thought dangerously; in fact, few could afford to do so; this new life was expensive and it had to be paid for cash down. Money had become much more important than it had ever been before. As a natural consequence the attitude towards the making of money changed. Any way was good as long as it worked, whether by honest manufacture or trade; by putting forward some new profitable device; by opening a mine; by raiding the foreigners; by lending money at interest. The Church might object, but if it pressed its objections, so much the worse for the Church, as the Reformation showed. Even magic acquired a new interest as a means to wealth and power, as we find in the story of Faust. Indeed natural magic was hardly distinguishable from science.[1.43; 4.4]

The marriage of the craftsman to the scholar

Just because they were essential to the making as well as to the spending of money, the technicians and artists were no longer so despised as they had been in classical or medieval times. The arts of ornament and display, painting, sculpture and architecture, flourished and were developed less massively but with far greater originality than in classical times. What was really new, however, was the respect given to the practical arts of spinning, weaving, pottery, glass-making, and, most of all, to the arts that provided for the twin needs of wealth and war—those of the miners and the metal-workers. The techniques of the arts were of more account in the Renaissance than in classical times because they were no longer in the hands of

slaves but of free men, and these were not, as they had been in the Middle Ages, far removed socially and economically from the rulers of the new society. In medieval Florence, for instance, the artists had been subordinate members of the major guild of doctors and spice-dealers, *Medici e Speciali*; the sculptors were lower down with the minor guild of the masons and bricklayers.[4.17] By the beginning of the sixteenth century, however, individual painters and sculptors could command the favours of popes and kings, though they often had to press hard to obtain payment for their work.

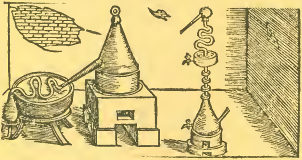
The enhancement of the status of the craftsman made it possible to renew the link between his traditions and those of the scholars that had been broken almost since the beginning of the early civilizations. Both had a great contribution to make: the craftsman could add to the old techniques of classical antiquity the new devices that had arisen during the Middle Ages; the scholar could contribute the world views, the ideas, and possibly most of all, the logical methods of argument derived from the Greeks by way of Arabic and scholastic philosophy, and the newly evolved methods of computation. The combination of the two approaches took some time to work out, and spread rather gradually at first through the different parts of knowledge and action. But once the constituents had been brought together there was no stopping the combination—it was an explosive one. The intellectual task of the Renaissance was essentially the rediscovery and mastery of the world of art and Nature.

The world surveyed

The Renaissance abounded in great descriptive works covering between them the whole field of human experience. The extent of its interest appears in the achievements of the one man who was himself the epitome of the age—the great universal engineer, scientist, and artist, Leonardo da Vinci. Its two greatest triumphs are the clear statement of the system of the heavens with the sun as centre, the system of Copernicus in his *De Revolutionibus Orbium Coelestium*,[4.84] and the first complete anatomy of the human body pictured in the *De Humani Corporis Fabrica*[4.109] of Vesalius, both published in the same year, 1543. These were the first pictures of how the heavenly spheres or the human body would appear to those who had eyes clear enough to see for themselves, and not through the spectacles of

a

b



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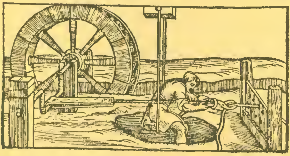


FIG. 8.—RENAISSANCE SCIENCE AND TECHNOLOGY

(*a*) Assayers' laboratory with cupels.

A known weight of ore is mixed with pure lead. This is burnt to dross in the furnace. The resulting bright bead of silver is again weighed, indicating quantitatively the yield of metal from the ore (pp. 86, 270).

(*b*) Stills for producing strong spirits.

On the right a reflux condenser, in which the weaker spirits are cooled and run back; on the left a spirit still with worm condenser immersed in a large bowl of water (pp. 239, 417).

(*c*) Mechanical wire-drawing.

A water-wheel drives a crank which on every half-turn draws the wire through the draw-plate (p. 233). From Biringuccio's *Pirotechnia.*

ancient authority. They were put forward and accepted at the outset by a new lay society that was also learning to see and experience for itself. It was only later, when the political consequences of the new vision began to be apparent, that authority took fright and tried, too late, to shut it out.

The great works were accompanied by many others in diverse fields of art and Nature which had been neglected by the Ancients. Such for instance was the *Pyrotechnica* [4.91] of Biringuccio (1480–1539), describing the metal, glass-working, and chemical industry; and *De Re Metallica* [4.14] of Georg Bauer or Agricola (1490–1555), probably the finest technical treatise ever written, for it described not only minerals and metals but also the practice and even the economics of mining. Later there were to appear in such books as those of Gesner (1516–65), Rondelet (1507–66), and Belon (1517–64) many magnificent descriptions of animals and plants, both of the old and the new worlds.[4.44; 4.21] To these may be added the almost innumerable accounts of the explorations of new lands, including Amerigo Vespucci's *Letters* [4.110] in 1504, which was rather inconsequentially to give the new-found continent its name, and Pigafetta's first account of Magellan's voyage round the world in 1519–22.

The opening phase of the Scientific Revolution was one of description and criticism rather than constructive thought. That was to come later. First must come the exploration of wide horizons and the challenge to old authority. The pursuit of the arts and techniques furnished the positive incentives and the material means for the advancement of the new science. The religious controversies and conflicts shook the framework of orthodoxy, and allowed a few people to try to think for themselves. The new religious attitudes of individual judgment and immediate responsibility stemmed from the same need that was to give rise to science. They were essential preconditions for the triumph of capitalist economy. Before attempting to discuss the position and influence of science in Renaissance life it is first necessary to say something of the influence of the most important factors that affected it in this phase. These are principally those of art and technique, in particular the techniques of engineering and navigation.

7.2—*ART, NATURE, AND MEDICINE*

Renaissance art

The exaltation of visible and manual art, as against passive and detached contemplation, was the first characteristic of the Renaissance. Painting, sculpture, architecture, and music had, it is true, flourished throughout the Middle Ages. They had been the medium of transference of many of the techniques of classical times, particularly of chemistry and metal-working. They were, however, used as a means to an end, carried out by humble craftsmen or monks in the service of the Church, and to a much lesser extent in that of chivalry.

The social and economic importance of art in the Renaissance was, however, of a different order. Not only was far more spent on art, especially on painting, than in earlier ages, but for the first time the arts began to be valued for themselves. The artists came to serve the new merchant princes wherever they flourished, first in Italy, then in Burgundy, Flanders, and High Germany. There was an insatiable demand for more impressive and striking forms to set off the new style of life of the rich.[4.17] With it came the rise in status of the artist and the setting up in most of the cities of Italy of studios which were at the same time universities and laboratories. Art itself, while not ceasing to be traditional, became conscious and scientific. The artists set themselves new problems and found new material and intellectual solutions to them. At no other time in history have the visual arts had such an effect on the development of science, and it is probably no accident that this interest coincided with the very beginning of the most important transformation in the history of science.

Perspective and vision

The major directions in which the artists helped to found science were in the development of vision and *perspective*, in the interest in Nature and particularly in the *anatomy* of the human body, and in their employment in civil and military engineering. Leonardo da Vinci divided his time between all these interests and though he was the greatest he was by no means the only one to do so.

The first manifesto of the Renaissance art was the *Trattato della Pittura* by Leon Battista Alberti (1404–72) in 1434. He

was the son of a wealthy Florentine family exiled for political reasons. Yet he did not scorn to devote himself to art or to learn from manual workers: "He would learn from all, questioning smiths, builders, shipwrights, and even shoemakers lest any might have some uncommon or secret knowledge of his craft, and often he would feign ignorance in order to discover the excellence of others." [4.15] He was one of the first advocates of formal perspective—invented by Brunelleschi early in the fifteenth century. The main aim of painting was for Alberti the representation of three-dimensional figures in two dimensions. Accordingly he demanded of all painters a thorough knowledge of geometry, and used optical aids such as the *camera obscura* for landscapes and the rectangular co-ordinates net for plotting the field of vision. The basic metrical concept of three-dimensional space became almost an intuitive commonplace in the Renaissance, due to the realization of this programme by artists like Masaccio, Piero della Francesca, and Mantegna.

Leonardo da Vinci was only expressing a prevailing view when he called painting a science. In his treatise on painting published with his *Paragone* [4.114] he states categorically:

> The science of painting deals with all the colours of the surfaces of bodies and with the shapes of the bodies thus enclosed; with their relative nearness and distance; with the degrees of diminutions required as distances gradually increase; moreover, this science is the mother of perspective, that is, of the science of visual rays.

In answer to those who would condemn painting as semi-mechanical he argues, in flat contradiction to Plato (p. 125):

> Astronomy and the other sciences also entail manual operations although they have their beginning in the mind, like painting, which arises in the mind of the contemplator but cannot be accomplished without manual operation. The scientific and true principles of painting . . . are understood by the mind alone and entail no manual operation; and they constitute the science of painting which remains in the mind of its contemplators; and from it is then born the actual creation, which is far superior in dignity to the contemplation or science which precedes it.

Nature and man

The Renaissance saw the triumph of the movement of *realism* in art. Classical, and even more Byzantine, art had

been concentrated on ideal forms and the achievement of effect by traditional symbolism. Already in the Middle Ages forms drawn from Nature were beginning to creep in, as foliage and animals, from the sides of the pictures. The Renaissance added the same realism for the central human figures. All this required the most detailed observations of wild Nature—mountains, rocks, trees, flowers, beasts, and birds—and thus laid the foundation of a geology and natural history no longer derived from books and logic. Most of all, it required an *anatomy* of man himself to find the underlying mechanism of gesture and expression. Renaissance art was as little impressionistic as it was formal. The painter was exhorted by Alberti to consider the bones, then the flesh that knit them, and only last of all the draperies in which the figure was clothed. Leonardo in his practice and precept went farther. From the representation of the static figure he passed to the moving one, hence to *physiology* and *dynamics*. The representation of men or animals in motion was for him only the means to an end, the expression of the spirit or soul that animates the movement. All this required a profound study of the anatomy of the brain and internal organs, of which Leonardo's drawings have never been surpassed. The new anatomy that led up to Harvey's circulation of the blood owed almost as much to the artists as it did to the doctors.

Renaissance medicine

It is convenient to consider here the great contribution of the Renaissance to the biological studies that centred on medicine. The medical faculties of the Italian universities were the most outstanding exception to their general sterility and obscurantism (p. 218). Particularly in the University of Padua, the medical faculty had acquired the highest prestige and attracted the most brilliant minds. This did not notably help medical practice, for centuries had to pass before enough was known of chemistry and biology to apply science effectively in the battle with disease. It did, however, help enormously in the development of natural science.

The Italian doctors and the large number of foreign students that came there to study medicine were not isolated. They mingled freely with artists, mathematicians, astronomers, and engineers. Indeed many of them followed some of these professions themselves. Copernicus, for instance, was trained

and practised as a doctor, besides being an administrator and economist. It was these associations that gave to European, and particularly to Italian, medicine its characteristic descriptive, anatomical, and mechanical bent. The human body was dissected, explored, measured, set down, and explained as an enormously complex machine. The explanation was far too simple; most of what we know now of the function or evolutionary history of the organs was not and could not have been guessed at. Nevertheless a new *anatomy, physiology,* and *pathology*—we owe the last two terms to the great French doctor Jean Fernel (1497–1558)—essentially modern in character, were founded on direct observation and experiment and the hold of classical authority and magical tradition began to be broken.[4.87]

This work found its epitome in the great *De Humani Corporis Fabrica* of Andreas Vesalius, which was the most complete description of all the organs of the body. Yet it still lacked any serious criticism of the classical picture of Galen (p. 161) and was good anatomy in the service of bad physiology. Nevertheless, the school he founded in Padua in 1537 was to furnish the sequence of anatomists leading up to Harvey. Vesalius became physician to the Emperor Charles V. His rival, Francis I of France, had as his surgeon a man who contrasted with Vesalius in many ways, Ambroise Paré (1510–90). He was a real craftsman, unlettered, writing in colloquial French of what he saw with his own eyes and did with his own hands. He revolutionized the treatment of wounds, particularly the gunshot wounds that became so common in the deadly wars of the time.

The engineers : Leonardo da Vinci

The professions of artist, architect, and engineer were not separated in the Renaissance. The artist might be called on by his town or prince, or might offer himself, to cast a statue, build a cathedral, drain a swamp, or besiege a town. The master craftsman had always had to know the properties of materials and the means of handling them. The artist of the Renaissance had to know all that and much more: he had to instil into his work geometry and mechanics in the conscious imitation of antiquity. It was in this field that Leonardo da Vinci, supreme as he was as an artist and a naturalist, showed his greatest ability. In recommending himself to the Duke of Milan, for instance, he cites a number of military devices he can

make and adds at the end, " In painting I can do as well as another." [1.3] His note-books show how keenly he studied the operations of metal-workers and engineers and how he himself became the first great master of *mechanics* and *hydraulics*. His greatest attempt, though doomed to failure, was trying to achieve *mechanical flight*—a masterpiece of engineering research, combining observation of birds with the making of models, calculations, and full-scale trials.[4.66; 4.113]

The study of the almost innumerable mechanical devices proposed and drawn by Leonardo, from rolling-mills to mobile canal cutters, brings out another aspect of the tragedy of his genius.[4.9] He could invent machines for almost any purpose and could draw them incomparably well, but hardly any of them, and none of the most important, would have worked even if he could have found enough money to make them. Without a quantitative knowledge of statics and dynamics, and without the use of a prime mover like the steam-engine, the Renaissance engineer could not, in fact, eve- advance beyond the limits set by traditional practice. He did not so much affect the development of the machine as impress on the learned world the idea that the operations of Nature could be explained by machinery.

Leonardo da Vinci illustrates in his life and works both the hopes and the failings of the Renaissance.[4.22] Trained as a painter, his many gifts brought him as a youth the patronage of the great at the most brilliant period of Italian art. But he was not satisfied with the practice of painting; he wanted at the same time to understand the underlying nature of what he painted and of the light by which he saw it. Hence his multiple studies on optics, anatomy, animals, plants, and rocks. At the same time he was impressed more and more with the importance of movement and force. It was to realize his ideas in practice that he put himself in the service of the most powerful prince of his time, Ludovico il Moro of Milan, but the shadow of war hung over him and Leonardo could achieve very little there. After the fall of Milan in 1499 Leonardo was forced to become a wanderer—for a while with Cesare Borgia on his campaigns, then in the service of the city of Florence and of the Pope, to die finally as an exile and pensioner of Francis I of France.

All the time he strove to penetrate more deeply into the underlying meaning of Nature and society. In this he was helped by having had no university education and so having

less to unlearn; but for the same reason he had neither the systematic approach nor the mathematical skill to follow out his ideas or to convince others of their truth. He left no school and was an inspiration rather than a guide.

Renaissance technology

The greatest advances of Renaissance technology were in the closely linked fields of mining, metallurgy, and chemistry. The need for metal led to the rapid opening up of mines, first in central Germany and then in America. The German mines were the nurseries of capitalist production. Throughout the Middle Ages mining was largely a series of one-man or small partnership ventures carried out by "free miners" who were their own prospectors, and who were taxed and protected from minor feudal interference by king or prince.[4.106] With larger-scale mining they came together in ***companies*** and divided their takings into ***shares***. Already in the fifteenth century shares were being taken up by sleeping partners who helped to provide the money for the increasingly costly gear. As mines grew deeper, pumping and hauling gear became more essential. Agricola of the ***De Re Metallica*** was officially a mining doctor in Bleiberg (lead hill) in Saxony, but he also held shares in some of the most profitable mines. The experience gained in power transmission and pumps was the starting point of a new interest in mechanical and hydraulic principles which was to have manifold effects in the Scientific and Industrial Revolutions. With the decay of mining in Germany that set in with the wars of religion, the German miners and metallurgists were dispersed to Spain; to the New World; most important of all, to England, where they provided the technical foundation for her future wealth.

Metallurgy and chemistry

The smelting of metals was the real school of chemistry. Extensive mining was bound to bring to light new ores and even new metals like ***zinc, bismuth*** (golden metal), ***cobalt*** (from kobold, the mine elf), and Kupfer***nickel*** (false copper). The ways of separating and handling these had to be found by analogy and corrected by bitter experience; but in doing so a general theory of chemistry, involving oxidations and reductions, distillations and amalgamations, began to take form, at first implicitly. Assaying, to find the yield of an ore in precious metal, is only

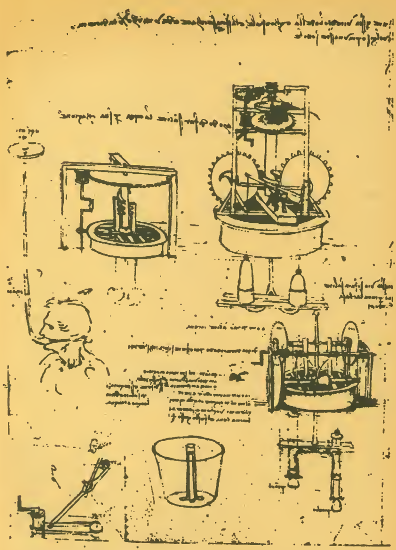


FIG. 9.—RENAISSANCE TECHNOLOGY: LEONARDO DA VINCI

Sketches for machinery, mostly double-acting force-pumps, showing ingenious devices of interrupted screws and spiral cam drives (p. 268).

smelting on a small but definite scale. It became the basis for chemical *experiment* and chemical *analysis* (Fig. 8, p. 263).

The host of new metallic substances could not but have physiological effects, mostly bad, but some good, on those who worked on them. Girls in the mining districts, for instance, used arsenic for improving their complexions. Metallic compounds began to be introduced into medicine on account of their violent effects on the body and to break down the reliance on traditional herbal simples. Particularly decisive was the use of mercury, where ancient herbs proved useless, to cure the new and terrible disease of syphilis brought back by Columbus' sailors.

Paracelsus and the doctrine of spirits

Philippus Aureolus Theophrastus Bombastus von Hohenheim (1493–1541), who called himself Paracelsus to show his superiority to Celsus the great doctor of antiquity, was the intemperate and enthusiastic founder of the new school of iatro-chemists (chemical doctors). He publicly burnt the books of Galen and Avicenna in the market-place of Basle, and in the real protestant spirit proclaimed the supremacy of direct experience over any authority. Though he drew on the old traditions of alchemy transmitted by the Arabs and by Raymond Lull (p. 221), he was able to transform them and change their direction. To the old opposites of *sulphur* and *mercury* he added the neutral *salt*, thus establishing the *tria prima*—rival elements to Aristotle's four (p. 144)—as the foundation to his *spagyric* art of chemistry, which abandoned the search for gold in favour of the search for health.

Paracelsus' approach to chemistry was frankly animistic. The doctrine of the operation of invisible agencies connected with all self-moving or living activities is one of the oldest of human ideas, probably originating far back in the Old Stone Age. It was associated with the *breath* which came first to every animal at birth and departed with death. The number of words in our language, borrowed from many others, denote the wide ramification of this idea: animal, afflatus, aspiration, ghost, inspiration, psyche, spirit, soul. Air itself was a kind of spirit and its working in bodies, as shown by bubbles, a sign of an active *fermentation*. The crucial process of chemistry, distillation, was essentially a means of capturing the invisible spirits that rose from a boiling liquid. That such spirits were

indeed powerful was only too evident from the effect of drinking them (p. 239).

All the operations of the body, according to the Galenic physiology, were performed by several distinct spirits or souls: the vegetable or natural spirit, seated in the liver, presided over the digestion of food; on meeting the vivifying breath in the heart, this became the vital spirit which was spread by the arteries throughout the body; in the ventricles of the brain this in turn was refined into the animal spirit, which, passing through the nerves, gave motion to all the body. Paracelsus, though he rejected Galen, was even freer in his adoption of the concepts of spirits. He pictured spirits—*archæi*, like the little kobolds that haunted the mines—presiding over the various internal organs—stomach, liver, and heart—just at the time when the directing angels were being banished from the heavenly spheres. Nevertheless, owing to the intrinsic complexity of chemistry, it was this intuitive and mythical approach rather than the rational, mechanical one that was to be most successful in advancing chemistry until its revolution in the eighteenth century, and Paracelsus had an undisputed place as the founder of modern chemistry. Even his *archæi* have returned in numbers far greater than he imagined them as the enzymes of modern biochemistry (pp. 616 ff.).

Metallic ores were not the only minerals that occupied Renaissance chemists. Some, like Bernard Palissy (1510–*c.* 1590), studied earths with the object of finding new glaze for pottery, at a time when European potters were just beginning to catch up with the technical triumphs of the Persian potters. It was still long before they could imitate Chinese porcelain or "china" as we still call it. Of far greater economic importance was the concern with alum, an essential material in the cloth and leather industries. The possession of alum mines provided ready cash for the Papacy, which founded the first chemical trust, the Societas Aluminum, in 1462.[3.38] Unfortunately papal alum was dear, and the effort to enforce the monopoly by threats of hell-fire was another reason impelling the clothiers of the North to favour the Reformation. In the celebrated indulgences issued by the popes to pay for the building of St Peter's, and which led to Luther's defiance of Rome, we find among the few crimes for which even the indulgence could obtain no forgiveness was the traffic in alum from rival sources.

Another great chemical development was in the art of

distillation, which was so expanded and improved that it underwent no further serious change until well into the eighteenth century. Not only were strong spirits drunk on a large scale in Europe, but they proved to be second only to gunpowder in persuading ignorant savages to give up their lands and even their bodies. By the end of the Renaissance the chemical laboratory, with its furnaces, retorts, stills, and balances, had taken a shape that was to lead without any radical change to the laboratories of today (Fig. 8, p. 263).

7.3—*NAVIGATION AND ASTRONOMY*

Voyages and discoveries

The technical developments in mining and metals owed little to science, though they gave much to it. It was otherwise with the great voyages that were to open the whole world to European capitalist enterprise. These were the fruit of the first conscious application of astronomical and geographic science to the service of glory and profit. It was natural that the Italian and German cities—Venice, Genoa, and even inland Florence and Nürnberg—with their widespread trade, should take the lead on the theoretical side. There was a resurrection and extension of Greek geography brought up to date by old travellers' reports such as those of Marco Polo and Rubriquis in the thirteenth century and by the results of recent ocean voyages. At the same time the Italians and Germans improved the application of astronomy to navigation, and initiated a drive for astronomical tables accurate and simple enough to be of use to sailors and for maps on which courses could be plotted.

The practical side was primarily the concern of the Portuguese and Spanish sailors, who combined the last effort of the Crusades with a practical eye for sugar plantations, slaves, and gold. Theory and practice met at the Court of Prince Henry the Navigator (1415–60) at Sagres, where Moorish, Jewish, German, and Italian experts discussed new voyages with seasoned Atlantic sea captains. A great revision of the Alphonsine tables (p. 223) was carried out by Peurbach (1423–51) and by his pupil Regiomontanus (1436–76), who worked in Nürnberg and was later assisted by Albrecht Dürer. In this work they used the old Ptolemaic system but simplified the calculations by means of the trigonometry of Levi ben Gerson (p. 225), thus going back to the Arabs and by-passing the

whole medieval mathematical effort. These tables and methods were of immediate use to the ocean navigators armed with Gerson's cross-staff. In the late fifteenth century the tight monopoly of eastern trade by the Turks made it a tempting idea to break into the Indian Ocean by some other way than the Red Sea. The theorists argued about two possible alternative routes. The most obvious, and one that could be attempted step by step, was to round Africa. This was the way favoured by the Portuguese. It was successfully accomplished in 1488, though India was not reached by Vasco da Gama till 1497. It was by no means certain in advance that it could be done because the land might reach to the Pole, but there were legends that it had been done by the Carthaginians and there might be good pickings on the way.

Christopher Columbus and the New World

The other project which was canvassed among the astronomers and theoretical geographers such as the Florentine, Toscanelli (1397–1482), was to sail westward over the untravelled ocean to find China at the other side of the round world. But to discuss such a hypothesis was a very different thing from making the actual attempt of sailing straight out to sea. In popular imagination anything might happen to such adventurers. They might sail on for ever; they might fall over the edge of the world. The one thing that no one foresaw was that there might be a continent in the way. The man who was willing to make the attempt has always been reckoned the prince of navigators and the most fortunate of explorers, " A Castilla y a Leon, Nuevo Mundo dió Colon," though he got little but trouble for it himself. Columbus was very far indeed from being a scientist or having any clear idea of what he was trying to do.[4.49] What he did have was the mystical inspiration that he could, by sailing over the ocean, discover new islands, even Cathaya, or rather, that he was a chosen vessel—Christophoros, the Christ carrier—destined for the discovery of the vision of the apocalypse of " A new heaven and a new earth." It was this vision, part religious, part scientific, that gave him the power, as a penniless man, to secure in the end support for his enterprise. It was something that could not have been thought of before and it was difficult enough to do even in the stirring and adventurous fifteenth century. Columbus had to hawk his idea for ten years round the courts of Portugal, Spain, England,

and France, being turned down by one expert committee after another. At last it was only by backstairs influence that he got permission to sail with a 100-ton ship and two pinnaces, but holding a contract assuring him of the title, Admiral of the Ocean Sea, and heavy royalties if he should find new land. The contrast between the successive expeditions of the Portuguese round Africa, and of Columbus venturing everything to sail straight across the Atlantic, is typical of that between the technical advance, depending on a steady improvement of tradition, and a scientific one which uses reason to break radically with tradition. For however mystical the internal motives of Columbus himself, the support he received for his voyages was given on the strength of a practical assessment of the return to be expected from the verification of a scientific hypothesis.

Columbus never knew he had discovered a new continent, and it got its name years later from that of the Florentine, Amerigo Vespucci, a learned friend of Leonardo, who was more successful in writing up his discoveries. It was left in the end to the Portuguese, Magellan, in the service of Spain, to complete the proof by showing how to sail round the world. Magellan himself never completed the voyage, being killed in the Philippines. The first man to return to his home after sailing round the world was his Malay slave.

Economic and scientific effects

The economic effects of the great navigations were both immediate and lasting. The short-circuiting, by an open sea route, of the traditional Arab overland and transhipping trade that had been so rewarding to them and to the Turks, brought immense profits to the Portuguese while ruining the Venetians. Later, the exploitation of the mines and the sugar and tobacco plantations of America by means of slave labour snatched from Africa was to bring in a larger and more stable income to Spain and the other colonial powers. Owing to the backwardness of the Spanish economic system this wealth, however, did not stay in the country, for both the exploitation of mines and of trade were in the hands of foreigners, and went to furnish the capital for the industries of Holland and Britain.

The effects on science were also decisive. The success of the early voyages created an enormous demand for shipbuilding and navigation. It brought into being a new class of intelligent, mathematically trained craftsmen for compass, map, and

instrument making. This was the beginning of a scientific public, and furnished both a training ground and a livelihood for intelligent youths of all classes. Navigation schools were founded in Portugal, Spain, England, Holland, and France.[4.101] The motion of the stars now had a cash value (p. 292) and astronomy stood in no danger of being neglected, even after astrology had gone out of fashion.

At the same time the twin discoveries of the old and wealthy civilizations of Asia, and the new world of America, with all their strange customs and products, made the classical world seem provincial and encouraged men with the knowledge that they had achieved something new which the Ancients had not even been able to think of. The new field, now opened to observation and description, needed new methods to analyse it. The navigations represented indeed as great a break-through in the sphere of the intellect as they did over the sphere of the earth. The initiators of the Renaissance hoped and worked for a new age. By the mid-sixteenth century they could feel they had achieved it. The humanist, Jean Fernel, physician to the King of France, and the first man of modern times to measure a degree of the meridian, expresses the new spirit in his *Dialogue* in about 1530. In justifying new ways in medicine he says:

> But what if our elders, and those who preceded them, had followed simply the same path as did those before them? . . . Nay, on the contrary it seems good for philosophers to move to fresh ways and systems; good for them to allow neither the voice of the detractor, nor the weight of ancient culture, nor the fullness of authority, to deter those who would declare their own views. In that way each age produces its own crop of new authors and new arts. This age of ours sees art and science gloriously re-risen, after twelve centuries of swoon. Art and science now equal their ancient splendour, or surpass it. This age need not, in any respect, despise itself, and sigh for the knowledge of the Ancients. . . . Our age today is doing things of which antiquity did not dream. . . . Ocean has been crossed by the prowess of our navigators, and new islands found. The far recesses of India lie revealed. The continent of the West, the so-called New World, unknown to our forefathers, has in great part become known. In all this, and in what pertains to astronomy, Plato, Aristotle, and the old philosophers made progress, and Ptolemy added a

great deal more. Yet, were one of them to return today, he would find geography changed past recognition. A new globe has been given us by the navigators of our time.[4.87.17]

The Copernican revolution

It is no accident that it was in the field of astronomy, so closely related to that of geography, that was to come the first and in some ways the most important break in the whole ancient system of thought. This was the clear and detailed exposition by Copernicus of the rotation of the earth on its axis and its motion around a fixed sun. Descriptive astronomy was the only science at that time which had accumulated enough observations and developed mathematical methods accurate enough to permit hypotheses to be set out clearly and tested numerically. Also, as we have seen, it was a centre of renewed interest both for its old astrological and its new navigational use. These in themselves might well not have led to any radical advance. Professional astronomers like Peurbach (1423–61) and Regiomontanus (1436–76) found the old methods, with minor improvements, good enough for them. Nevertheless it is to them and the Renaissance spirit which led them to seek for Greek originals that we owe the new astronomy. Peurbach was in the service of Cardinal Bessarion (*c.* 1400–1472), the Byzantine humanist, and was engaged by the Pope in the reform of the calendar.

What Copernicus added was the new critical spirit, an appreciation of æsthetic form and the inspiration of newly edited texts which could also be used to balance one ancient authority against another. For, as we have seen, the idea of the rotation of the earth was by no means a new one. It goes back to the very foundation of Greek astronomy and was stated in so many words by Aristarchus in the third century B.C. (p. 157). It had always remained as an alternative—though paradoxically absurd—view of the motion of the stars; for it was self-evident that the earth did not move, while the sun, moon, and stars could be seen to do so. Courage as well as science would be needed to upset the common-sense view. The man who was to dare to do this, for all his retiring nature, had plenty of courage and, as a Renaissance humanist, had all the incentives to achieve this decisive break with the past.

Nicholas Copernicus was born at Torun in Poland in 1473, was educated at Bologna for astronomy, at Padua for medicine,

and at Ferrara for law, and spent most of his life as canon of Frauenburg. As this cathedral town was situated in the disputed territory between the Teutonic knights and the kingdom of Poland, he had much to do with war and administration; but his main interest was always astronomical, and he devoted the whole of his private life to the effort to find a more rational picture of the heavens, which he set out in final form in his book *On the Revolution of the Celestial Orbs* which was printed only in the very year of his death in 1543. In it he postulated a system of spheres centred round the sun rather than the earth, assuming the rotation of the earth and showing in detail how this could account for all astronomical observations.* His reasons for this revolutionary change were essentially philosophic and æsthetic.[3.1] Speaking of his sun-centred system and its implication of the almost infinite distance of the stars he writes:

> I think it is easier to believe this than to confuse the issue by assuming a vast number of Spheres, which those who keep Earth at the centre must do. We thus rather follow Nature, who producing nothing vain or superfluous, often prefers to endow one cause with many effects.[4.84.19]

And then after describing the planetary orbs one after another he ends:

> In the middle of all sits Sun enthroned. In this most beautiful temple could we place this luminary in any better position from which he can illuminate the whole at once? He is rightly called the Lamp, the Mind, the Ruler of the Universe; Hermes Trismegistus names him the visible God, Sophocles' Electra calls him the All-seeing. So the Sun sits as upon a royal throne ruling his children the planets which circle round him. The Earth has the Moon at her service. As Aristotle says, in his *de Animalibus*, the Moon has the closest relationship with the Earth. Meanwhile the Earth conceives by the Sun, and becomes pregnant with an annual rebirth.

Here also we see both a return to a most ancient, indeed a magical, view of the universe and an exaltation of the central monarchy, *le Roi Soleil.*

The presentation of the *solar system* took some time to have any effect. A few astronomers appreciated it as a means of improving calculations. The Prussian tables were prepared in 1551

on the basis of the Copernican system, but few believed it was really true. Besides being repugnant to common sense, there were many objections that affected the learned, particularly as to how the earth could go round without producing a mighty wind or deflecting the fall of shot. These were only finally removed by Galileo (p. 297).

Nevertheless the mere idea of an open universe, with the earth but a small part of it, was shattering to the old image of closed concentric crystalline spheres, divinely created and maintained in motion. If there were new worlds on the earth, might there not also be in the sky? This was the heresy for which Bruno was to die.

The achievement of the Renaissance

The first phase of the Scientific Revolution was mainly a destructive one in the field of ideas, though illuminated by the one brilliant constructive hypothesis of Copernicus. Not only in astronomy but also in other fields of interest—in anatomy, in chemistry—the old ways of thought were proving inadequate and unsatisfying. The men of the Renaissance, even if they had found the solutions to few of the problems they had raised, had at least cleared the ground for the solution of the remainder in the great struggle of ideas of the succeeding century.

In the use of science, by contrast, the Renaissance marked an era of decisive achievement. The scientific effort of the early Middle Ages had faded away, largely, as has been suggested, because no practical use could be found for it. The achievements of the Renaissance navigators did provide just what was necessary—a secure and growing field of application. And this field required astronomy and navigation, just those parts of science best preserved from classical times and most actively maintained in the service of astrology and calendar-making. Further supports were to be provided for the science of mechanics in the development of machines, and for that of dynamics in the development of gunnery. From now on science was secure; it had become a necessity for the most vital, active, and profitable of enterprises—for trade and war. Later it could extend its services to manufacture, agriculture, and even medicine. The overall importance of the Renaissance was that it marked the first break-away from the economy, the politics, and the ideas of the feudal Middle Ages. Most of the

constructive work had still to be done, but there was to be no turning back. Science was beginning to make its mark on history.

7.4—*THE SECOND PHASE: SCIENCE DURING THE FIRST BOURGEOIS REVOLUTIONS 1540–1650*

The period roughly from 1540 to 1650 has no convenient name in history. It has been called the Counter-Renaissance,[4.4] but this would indicate a far greater degree of reaction to the earlier phase than actually took place. It includes the Counter-Reformation, with the Baroque style that was its visible expression, the Wars of Religion that raged in turn in France (1560–98), in the Low Countries (1572–1609), and in Germany (1618–48), and the establishment of the States General of Holland in 1576 and the Commonwealth of England in 1649. Of these events it was the last two that were to have the greatest ultimate significance. They point to the political triumph of the new bourgeoisie in the two countries in which was concentrated the bulk of the world's trade and manufacture.

In science the period includes the first great triumphs of the new observational, experimental approach. It opens fresh from the first exposition of the solar system by Copernicus and closes with its firm establishment—despite the condemnation of the Church—through the work of Galileo. It includes in its scope Gilbert's description in 1600 of the earth as a magnet and Harvey's discovery in 1628 of the circulation of the blood. It witnesses the first use of the two great extenders of visible Nature, the telescope and the microscope.

Economically the century was dominated by the cumulative effects of the navigations, which by then involved a trade comparable with the old internal trade of Europe. It was specially marked by the great increase in prices brought about by the influx of American silver. The breakdown of feudal land-holding in western Europe, especially in Holland and England, had thrown on the market landless people, and, at the same time, the real wages of hired workers were seriously depressed. This had the effect of lowering the cost of products in a period of rising prices and increasing markets, and at the same time of providing an abundant labour force for manufacturers. The result was an unprecedented increase in the

wealth of those traders and manufacturers who were on the new oceanic trade routes and could draw on new resources and supply new markets.[4.3; 4.7] The combined effects of the change in trade routes and wars were to ruin the economy of Germany, which had been the most progressive part of Europe in the early sixteenth century.

The loss at the old centre was more than made up on the periphery. The new economic centre of Europe, and by then indeed of the world, was in the lands round the North Sea, first Holland, then England and northern France. There, unlike the other maritime countries Spain and Portugal, where conditions remained feudal, manufacture could be combined with trade. The German and Italian craftsmen emigrated and rapidly spread the technical and artistic achievements of the Renaissance to the now dominant northern nations. At the same time the need for corn to feed the growing populations of Holland and England, and for flax, timber, pitch, and iron for their shipping, stimulated the economic development of the Baltic countries, where Denmark, Sweden, Poland, and Russia in turn began to emerge as independent powers.

The moving spirits and the main beneficiaries of this second phase of theeconomic revolution were the merchants of Holland and England, who were backed by flourishing agriculture and fisheries. Wealth brought political power to the bourgeoisie, but this did not come easily. It took years of struggle and open warfare before the kings, first of Spain and then of England, were forced to realize that they could no longer hold their wealthy Dutch or English subjects under feudal conditions that hindered them in the pursuit of profit. The ostensible reasons for this struggle were religious, and this had at least the justification that the political and economic convictions and practice of the new bourgeoisie were more naturally expressed in Calvinist than in Catholic or even in Lutheran terms.[4.99]

The advance of technology

Technically the century was one of steady advance in scale and performance, without any of the revolutionary innovations that characterized the centuries before and after. Agriculture was still the predominant occupation and woollen cloth-making the major industry. Nevertheless change was in the air. Shipbuilding improved with experience and with it navigation. The increase in trade and the lowering of trans-

port costs led to a much wider distribution of wealth among the bourgeoisie. Rare luxuries, such as silks and glass, became commodities, while new products from east and west, such as cottons, porcelain, cocoa, and tobacco, began to come into European markets. Painting, in the Flemish and Dutch schools, began to leave the service of religion and the exaltation of nobility to portray ordinary people eating, drinking, and making merry. It is in this time that the Dutch set the standard of bourgeois *comfort* in town and country houses, and invested good money in gardens and fields (p. 333).

The blast-furnace and cast iron

An ultimately more momentous change was occurring almost unperceived in the methods of production of less spectacular goods, particularly of iron. It was in this period that the transformation in iron metallurgy that had been maturing in Europe since the fourteenth century first began to have a decisive effect. Cast iron had been known in China since the first century B.C. (p. 102), but its appearance in Europe seems to have been quite independent. Its production is typical of a crucial change brought about by a mere increase in the scale of operation. For 3,000 years iron had been made by low-temperature reduction with charcoal in small bloomery furnaces, leaving the iron in a pasty mass (p. 101). Throughout the Middle Ages these furnaces came to be made larger and the blast for them was provided by bellows, ultimately driven by water-power. Occasionally the temperature was high enough to melt the iron and turn the malleable " bloom " into an intractable " bear." [4.96] Then, first in the Rhineland in the fourteenth century, came the idea of running off the iron on to the floor in front of the furnace into a hollow which soon became the " sow " with its litter of " pig " iron. This pig iron was at first difficult to refine and improvement was slow; but, as the knowledge of the process spread, bloomeries gave way to the new *blast-furnaces*, and by the end of the sixteenth century iron began to be poured out by the ton instead of being beaten out by the hundredweight.[5.2]

The limitation that dear iron had imposed on all techniques was rapidly removed, but a new bottle-neck appeared, caused by the shortage of the wood charcoal needed to smelt the larger quantities of iron. Old-established iron regions, like the Weald of Sussex, lost their predominance, which passed to Sweden

and Russia with their large supplies of timber. Iron, indeed, was a major factor which, through trade and war, brought them into world economy. Cast iron was used first and foremost for weapons, especially cannon, once the bronze bell-founders' art could be applied to it. England early acquired a reputation for good cannon and they were marketed on strictly business principles. The guns of the galleons of the most Catholic King of Spain and those of the infidel Bey of Algiers were as likely as not to have been cast in Sussex.[4.96]

The use of coal

The shortage of wood for iron-smelting was only one reason among many for the acute timber crisis that affected Holland and England in the late sixteenth century. General mercantile prosperity raised the demand for timber—for ships and houses, for firewood, for salt-makers, soap-boilers, maltsters, as well as for domestic uses—far beyond the capacity of the local forests. Some could be imported, but a remedy lay ready to hand in the pit coal that had been worked from open seams in Northumbria and Scotland since Roman times, and had already found a distant market as sea coal in London and even on the Continent in the Middle Ages. It was pretty filthy stuff, but it came to be burnt by the citizens for fuel despite all laws prohibiting its use.

As the price of firewood soared in the sixteenth century, more and more uses were found for coal, and its production increased rapidly. In the seventy years from 1564 to 1634 the annual shipments of coal from Newcastle rose fourteenfold to nearly half a million tons.[4.73] Correspondingly more technical effort was put into mining it from deeper and thus more easily flooded pits. This led to the use of devices largely taken over from the metal mines of Europe—improved pumps and the wooden *rail way* for running the trucks out of the mines. Coal was indeed to solve the recurrent fuel crises that in the past had driven civilization further and further to uncut backwoods. From then on the centre of industry, and with it the centre of civilization, was to move towards the coalfields, where it was to be fixed for another 400 years at least. It was this, rather than any other factor, that was to lead to the industrial predominance of Britain. As that shrewd observer Daniel Defoe put it in his description of the West Riding of Yorkshire:

> . . . such has been the bounty of Nature to this otherwise frightful country, that two things essential to the business,

as well as to the ease of the people are found here, and that in a situation which I never saw the like of in any part of England; and, I believe, the like is not to be seen so contrived in any part of the world; I mean coals and running water upon the tops of the highest hills: This seems to have been directed by the wise hand of Providence for the very purpose which is now served by it, namely, the manufactures, which otherwise could not be carried on; neither indeed could one fifth part of the inhabitants be supported without them, for the land could not maintain them.

Neither in the technical innovations involved nor in the use of science can the industrial upsurge of the late sixteenth and early seventeenth centuries, which has been called the first Industrial Revolution,[4.7] be compared with the great Industrial Revolution of the eighteenth century. Nevertheless, we can see now that it was its essential prelude. Before it was conceivable or possible to change from a wood and water-power technology to an iron and coal one, the change had to be demonstrably necessary. It was the pressure of the demand of the first Industrial Revolution on the limited resources which had sufficed for the feudal economy of the Middle Ages that forced the search for new resources and new techniques.

The projectors : Simon Sturtevant

It was also that same pressure that finally altered the attitude towards novelty. Once profit was legitimate and novel methods could promise riches, novelty was to be embraced rather than shunned. This was the shop that sold the " new thinking cap " to which Professor Butterfield attributes the birth of modern science.[3.1] The late sixteenth and early seventeenth century saw the first of the race of *projectors*, later called *inventors*. These did not merely talk, as Roger Bacon had done, of wonderful new machines but offered to make them, for a consideration, and sometimes even did so.

Such a man was Cornelius Drebbel (1572–1634), who built a submarine which he showed in the Thames, but made a more profitable venture in introducing a scarlet dye. Such also was the forgotten and tragic figure of Simon Sturtevant, an eccentric clergyman who aimed higher—at nothing less than " the working, melting and effecting of Iron, Steele and other mettles with Sea Coale or Pit coale; the principall end of such

invention is that the woods and timber of our country might be saved" (from the preamble of his Patent *The Treatise of Metallica* (1612) [4.97]). What Sturtevant's secret was, or how he came on it, we may never know. The problem he set himself was not solved in practice for another hundred years (p. 429), but he has left us a most precious account, in many ways unsurpassed, of the technical and economic aspects of invention, written before the dawn of the new industrial age. Sturtevant begins with "Heuretica—the Art of inventions, teaching how to find the new and judge the old." This he further divides into an "Organick" part, comprising the fixed capital, and a "Technick" part, comprising the skill of the "Artizands." In his analysis of the processes of invention he distinguishes drawings, models (superficiall and real Moddles), working models, prototypes (the Protoplast), and finally the "Grand Mechanick," or full-scale production "set up after the form and type of the Protoplast in greatness, or with some profitable additions which later experience has taught." He was fully alive to development costs and the criteria of profitability, and had clear ideas as to the means of raising capital. Why then did he fail completely? It was not technical incapacity—he had already proved his worth by inventing pressed clay ware, which we use to this day. The reasons appear in the sequel to arise from the conditions of the time, which were quite unsuited for the kind of capitalist enterprise he foresaw with such surprising clarity.

Sturtevant estimated the annual yield of the iron monopoly at £330,000. He accordingly divided his enterprise into thirty-three shares; of these the King, Princes, and the favourite Carr received eighteen, Sturtevant himself received one, and the remaining fourteen were to be distributed among "those who shall adventure, joine or assist the work." What with the court rake-off it is not surprising that it all came to nothing. Two of the adventurers stole the patent from Sturtevant, got him outlawed, and then failed to work the process themselves, since the original patent is a model of obscurity when it comes to particulars.*

Modern industry could not arise from feudal conditions, or even from the prerogative of a Renaissance prince who, lavish in his expenses, was always short of money and always being cheated. The real technical advance was made by the small men building up their capital out of their profits. This they

could achieve only in the next century, when the privileges of kings, nobles, and corporations had been swept away (p. 429).

The new experimental philosophers

It was in this atmosphere that the new, half-awakened science of Europe was to grow to maturity. Despite widespread privilege and corruption it was not by any means an unfavourable one. Even the movement of the Counter-Reformation, which successfully checked and turned back the advance of Protestantism in Europe, had not the same effect on science. The Jesuits who directed it had the intelligence to realize that they were more likely to win souls by fostering science than by blindly opposing it. They accordingly entered fully into the scientific movement, particularly the new astronomy, and were even the agents for spreading it and setting up observatories in India, China, and Japan. At the same time they acted as watchdogs inside science to guard against any damaging effect it might have on true religion, and thus unintentionally gave an advantage to scientists in Protestant countries out of their control.

The fifteenth-century concentration of science in Italy was replaced by a wide diffusion over Europe, though Italian intellectual pre-eminence was for some time to outlast political and economic decadence; for Italy, the first of the countries of western Europe to break away from the feudal tradition, remained the centre of European culture long after she had lost her political and economic importance. That culture was a well-balanced one, since in Italy, at first alone in Europe, the universities had largely been won for the new learning. The professors were moreover courtiers, and were thus able to combine practical knowledge of the world and full acquaintance and contact with scholastic tradition. From whatever country new scientists came, whether from Poland, England, or France, it was in Italy that they acquired their knowledge and it was in Italy that they did much of their best work.

The new experimental philosophers, or scientists as we would now call them (p. 7), no longer formed part of the intense city life of the Renaissance; they appeared more as individual members of the new bourgeoisie, largely lawyers, like Vieta, Fermat, Bacon; doctors—Copernicus, Gilbert, Harvey; a few minor nobles—Tycho Brahe, Descartes, von Guericke, and van Helmont; churchmen, like Mersenne and Gassendi; and

even one or two brilliant recruits from the lower orders, like Kepler. In history they are made to figure as being isolated; but in reality they were, because of their very small numbers, always in far easier and quicker contact with each other than scientists of today, with their vast numbers and the pressure, publication delays, and increasing military and political restrictions to which they are subjected.

Scientific education: Gresham College

In Holland and in England there was even the beginning of scientific education, with a decided bent for navigation, in imitation of the Spanish and Portuguese schools of the first phase. The Flemings, Gemma Frisius (1508–55) and Gerard Mercator (1512–94), had shown the way in making accurate navigational charts. They were closely followed by English geographers, of whom the first, John Dee (1527–1608), though best known as an astrologer, was the friend and adviser of many of the great Elizabethan sailors and may rightly be claimed as the first British scientist of the new age. The first institute for teaching the new science in England was Gresham College, established in 1579 by the will of Sir Thomas Gresham (1519–79), one of the great London merchants, financial agent to the Crown, and founder of the Royal Exchange. He personified the union between merchant capital and the new science. Unlike the Collège de France of the earlier generation (p. 258), Gresham College was no mere humanist institution. Lectures were to be in English as well as Latin. Of its seven professors, two were appointed for the sciences of geometry and astronomy, and the latter was urged to lecture on instruments of navigation "for the capacities of mariners." [4.48] Gresham College was to be for over a century the scientific centre of England and was to house the Royal Society, which at first met in its rooms.

Most of the scientists of the period took for granted, what had been heresy in classical and medieval times, that science was primarily concerned with Nature and the arts and that it was its business to be useful. Most of them at one time or another were in State service and tried to justify their employment by practical inventions in peace and war. Their originality and individualism were only apparent. In most of their thought they necessarily relied on the same traditions, used the same methods, and were drawn to the same problems. These problems were

limited in number compared with either the qualitative Renaissance universalism or the systematic search of Nature of the succeeding phase of organized science. The main questions asked were those concerned with the working of the heavens, leading to the use of astronomy in navigation, with the movements of projectiles and machines, and with the gross mechanism of the human body. Their programme was no longer purely negative, as in the first phase of the Renaissance; they set out not so much to destroy the systems of Aristotle and Galen but to provide workable alternatives. In this they succeeded beyond all expectation, though the final synthesis was to be reserved for the age of Newton.

7.5—*THE JUSTIFICATION OF THE SOLAR SYSTEM*

The implications of the Copernican revolution took some time to sink in. It was welcomed most readily by professional astronomers because of its simplicity and as a means, though still far from an accurate one, of improving astronomical tables. Next came those who found in it a convincing illustration of the stupidity of the old, medieval, Aristotelian world view or who were inspired by the vision of an infinite universe which it opened up. Of these the most famous was Giordano Bruno (1548–1600).[4.90] Born in Nola near Naples, of fiery temperament and penetrating imagination, he soon quarrelled with the monastic order which he had joined and led a wandering life throughout Europe, disputing and publishing books and pamphlets in which he mingled Lullian mysticism with the idea of the plurality of worlds. His ability was such that he impressed magnates and scientists alike, but his sharp tongue made him more enemies than friends and he was kept always on the move. At last, venturing incautiously into Venice in 1592, he was betrayed and handed over to the Roman Inquisition, who burnt him to death eight years later for heresy. He was a martyr not so much to science as to freedom of thought, for he made neither experiments nor observations, but insisted to the end on his right to draw what conclusions he chose from the facts of science.

Bruno made people think and argue about the Copernican theory. For all the Catholics that his execution frightened, as many Protestants must have been encouraged. More solid arguments were needed, however, before the Copernican theory

could be established and profitably used. What the theory lacked in its first form was an accurate description of the orbits of the planets, which was to be the work of astronomers to provide, and also convincing arguments to justify the imperceptibility of the motion of the earth, a task which implied the creation of a new science of dynamics.

Uraniborg and Tycho Brahe

The first task was carried out by two remarkable men, Tycho Brahe (1546–1601) and his assistant, Johannes Kepler (1571–1630). Tycho Brahe, himself a Danish nobleman, was able to use enough influence with King Frederick II to build in 1576 the first really scientific institute of the modern world—Uraniborg—on the island of Hveen in the Sound from whose tolls Denmark drew most of its wealth. There, with specially made apparatus, he collected a series of exact observations on the positions of stars and planets that made everything that had been done before obsolete. He was influenced by Copernicus' work, but he preferred a system of his own in which the sun turned round the earth but the planets turned round the sun, which is, of course, the Copernican system relative to a motionless earth. In fact he chose the system that best fitted the observations without worrying about its physical absurdity. He had actually, without insisting on it, already shattered the Aristotelian system by demonstrating that the New Star of 1572 lay in the sphere of fixed stars, where by definition no change could take place. Tycho lived in a transitional time for astronomy, just when the old need for astronomical data, almost exclusively for astrological purposes and consequently subsidized only by princes, was giving way to a new need for more exact astronomical data for the use of navigators.

Kepler

Tycho's results became infinitely more valuable for the progress of science when they were worked over by Kepler. He was the son of poor parents and lived a life of continual struggles and frustrations, partly due to his own strange character. He was the first great Protestant scientist, though he worked for most of his life in Catholic lands. He combined in a most unusual way a fantastic imagination, deeply tinged with number magic, with a scrupulous integrity in the accuracy of his measurements and calculations. The major drive behind his work was a

mystical desire to penetrate the secrets of the universe, as witness the title of his first work, *Mysterium Cosmologicum*.[4.63] But he had to live, and, as he said, "God provides for every animal his means of sustenance—for astronomers He has provided astrology." He assisted Tycho in his last years in the crazy alchemical-astrological institute that the Emperor Rudolph II had set up in Prague. The presence of active and subsidized scientific research in sixteenth-century Poland, Denmark, and Bohemia was in itself a sign of the new economic development that these countries, on the fringe of feudal Europe, were then undergoing.

There Kepler tried to find the best way of representing planetary motions by a single curve. Copernicus had still stuck to circles and epicycles, but not only were these clumsy but they could not be made to fit the new accurate observations. Kepler found, after many failures, that the only explanation of the observed movement of the planet Mars was that its orbit was an ellipse with the sun as focus. The idea of elliptical orbits was not completely new; it had been suggested by Arzachel (1029–87) of Toledo in the eleventh century, but on quite inadequate data. Kepler succeeded because he came at a time when the data were exact enough to show that no circle or combination of circles would do, and not so late for them to be so exact that it was apparent that the orbits were not true ellipses but more complicated curves, which were to be explained only by Einstein.

The hypothesis of elliptical orbits, and the two other laws by which Kepler explained the speed of a planet in its orbit, not only removed the main astronomical objection to the hypothesis of Copernicus, but they also struck a mortal blow at the Pythagorean–Platonic view of the necessity of the heavens showing perfect—that is, circular—motions only, which even Copernicus had retained. These purely astronomical calculations of Kepler were not, however, the decisive element in producing the great revolution in men's minds leading to an altogether new view of the universe, though they were to be the observational basis of a quantitative, dynamical explanation which Newton was later to work out (pp. 334 f.).

The telescope

The step that was to prove decisive in securing the acceptance of the new view of the heavens was not to be any further extension

of astronomical calculation, appreciated only by experts, but a direct physical means available to all of bringing the heavens down to earth so that sun, moon, and stars could be more closely examined; in other words the invention of a telescope or far-seer.

The *telescope* was probably not itself a creation of science: it appears rather obscurely in Holland as a by-product of the manufacture of spectacles. Legend has it that it was about the year 1600 when some child in Lippershey's shop first looked through one lens at another in the window and noticed that it made things outside seem nearer. The fact that no scientific genius was required to invent the telescope shows that it was long overdue. The need for it had always existed, but nothing was done because it was not thought to be realizable. The means of making it had in fact been available for some 300 years. It seems, however, to have required the mere quantitative concentration of optical manufacture that went with the greater wealth of the sixteenth century to bring about its discovery by chance.

Galileo Galilei

The telescope was to prove the greatest scientific instrument of the age. The bare news of it reaching the ears of the professor of physics and military engineering at Padua, Galileo Galilei (1564–1642), determined him to make one himself and turn it on the heavens. Galileo was already a convinced Copernican, as well as being deeply interested in the movements of pendulums and the related problems of the fall of bodies. In the first few nights of observation of the heavens he saw enough to shatter the whole of the Aristotelian picture of that serene element. For the moon, instead of being a perfect sphere, was found to be covered with seas and mountains; the planet Venus showed phases like the moon; while the planet Saturn seemed to be divided into three. Most important of all, he observed that around Jupiter there circled three stars or moons, a small-scale model of the Copernican system, which anyone who looked through a telescope could see for himself.

With his keen sense of publicity and of the material value of his discoveries, which he found in no way incompatible with the pure joy of discovery, Galileo immediately tried to sell the titles of these stars in succession to the Duke of Florence (a Medici), to the King of France, and to the Pope, but the celestial honours

seemed too expensive to all of them. Later, when the more practical end of using their motion to determine longitude at sea occurred to him, he tried to sell the secret to the King of Spain and the States General of Holland, who had both offered prizes for the discovery of the longitude, but still found no takers.[1.3.187]

These attempts, however, were to Galileo mere side-shows. He sensed at once the really revolutionary character of the new observations. Here he had for everyone to see the very model of Copernicus' system in the sky. This was knowledge not to keep but to broadcast. Within a month, in 1610, he had published what was clearly a scientific best seller, *Siderius Nuntius*, i.e. "Messenger from the Stars," in which his observations were set out briefly and plainly. It created a great sensation and still it met with no immediately unfavourable reaction. The trial was not to be for another twenty-four years, and while a qualified condemnation of Copernican views was pronounced in 1618, it placed no obstacles to their being considered as a mathematical representation of the motions of the heavens. A few hard-bitten Aristotelians refused to look through the telescope, as they knew perfectly well what was in the heavens by the exercise of sheer reason. As long as reason and observation could be kept in different spheres of discourse there would be no trouble.

The fall of bodies: dynamics

But Galileo felt it was not sufficient to have verified by observation the æsthetic preference of Copernicus. It was also necessary to justify it by explaining how such a system could exist, and by removing the objections which both philosophy and good sense had raised to it in the past. It was necessary to explain how the rotation of the earth could occur without a mighty wind blowing in the opposite direction and how bodies projected through the air would not be left behind. This meant a serious study of bodies in free motion, a problem which had already become of great practical importance in relation to the aiming of projectiles.

By that time the impetus theory of Philoponos (p. 185), passed on by the Arabs and elaborated by the Parisian Nominalists (p. 221), was gaining acceptance. The projectile, on leaving the gun, was supposed to be endowed with an impetus or *vis viva* which for a while destroyed its natural propensity to fall

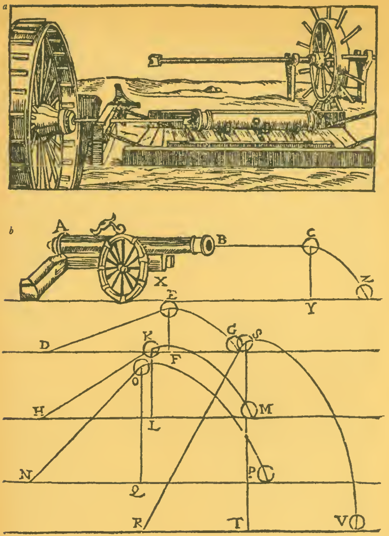


FIG. 10.—THE CANNON IN RENAISSANCE TECHNOLOGY AND SCIENCE

(*a*) Drilling cannon by water and hand power (p. 239).

From Biringuccio's *Pirotechnia.*

(*b*) The trajectories of cannon balls shot at various angles of elevation. The impetus theory is responsible for the straight first portion (p. 293).

From Cespedes' *Instrumentos Neuvos de Giometria,* 1606.

downwards. Tartaglia (1500–57), Benedetti (1530–90), and others in the sixteenth century had elaborated this explanation by inserting between the violent rise of the projectile and its natural fall a circular mixed motion producing a trajectory that for the mortar bombs of the period was not too bad an approximation. What it lacked, however, was any logical or mathematical justification [4.64] (Fig. 10).

Experimental physics

Galileo succeeded, where others had failed, in formulating a mathematical description of the motion of bodies. This was to be the major work of his life, expressed fully only in his *Dialogues on Two New Sciences,* published after his condemnation but implicit in the *Dialogue Concerning the Two Chief Systems of the World,* which was to be the immediate cause of his conflict with the Church. Galileo proceeded to question all the accepted views and to do so by the new method, the method of experiment. Whether or not in fact he dropped weights from the top of the tower of Pisa is not the essential point; we know that he used both the pendulum and the inclined plane to make accurate measurements of the fall of bodies.

These were almost but not quite the first experiments of the modern science. They differed from the experiments of the thirteenth-century scholars mainly in being exploratory rather than illustrative, and even more by their quantitative character, which could be fitted into mathematical theory. Galileo himself showed a transitional attitude towards his own experiments. He once stated that he carried them out not to convince himself but to convince others. He was superbly confident in his power to interpret Nature by reason. In this sense they were rather demonstrations than experiments. Nevertheless he really did carry them out, unlike the ideal, paper experiments which befog modern physics; and what is more, when they gave results he did not expect, he did not reject them but turned back to question his own arguments, thereby showing the essential humility before fact that is the hall-mark of experimental science.

The mathematical interpretation of Galileo's experiments on falling bodies here proved to be far more difficult than the experiments themselves. The idea that had to be grasped was that a body that was changing its speed all the time could have any particular speed at a given moment. As a matter of fact

Galileo went wrong to start with and assumed that speed was gained in proportion to the distance gone through by the body, whereas, as he himself was later to conclude, it depended directly on the *time* the body was falling.[4.64] To understand the falling of bodies, and consequently both the motions of cannon balls in the air and of the moon in the sky, it was essential to grasp the very difficult physical idea of the velocity at a moment of time. This corresponds to the mathematical idea of a differential, dx/dt: the ratio of two quantities that remains constant even if the quantities themselves become vanishingly small. Galileo used these ideas without precisely formulating them. By combining exact experiment and mathematical analysis, he solved the relatively simple problem of the fall of bodies, showing that in the absence of air they would follow a parabolic path. In doing so he provided the first clear example of the methods of modern physics, which were to have such an extraordinarily successful development in succeeding centuries. Indeed the exact physical method he initiated has, until very recently, been taken as *the* basic method of science, one to which all other science may in the end be reduced.

The renaissance of mathematics

The achievement of Galileo and Kepler was possible because they were masters of the new *mathematics* that had blossomed with the Renaissance. Vieta (1540–1603) had taken the decisive step of making all algebraic argument *symbolic* by using letters for both known and unknown quantities not only in algebra but also in trigonometry. This purely technical device enormously speeded up calculations and removed the confusion that words inevitably induce. Thanks to his work, as well as that of Cardan (1501–76) and Tartaglia, algebraic methods could be employed for dealing with any problem where quantities could be reduced to numbers. The old Greek geometry still retained its prestige, especially since the recovery of the works of Archimedes, first edited by Tartaglia in 1543; but numerical calculations could be dealt with far more easily by the methods of algebra. An enormous practical step forward was registered when Simon Stevin (1548–1620) introduced decimals in 1585, and Napier (1550–1617) logarithms in 1614. By shortening computations by a large factor it effectively multiplied the number of working astronomers and physicists.

To complete the chain of argument it was necessary for Galileo to link mathematics with mechanics. How to do this was a major preoccupation throughout his whole scientific life. Leonardo was groping after a quantitative approach to mechanics; Galileo, with the advantages of better experiments and a more applicable mathematics, fully grasped it. He became one of the founders of scientific engineering. Another was the same Simon Stevin of Bruges, the first great engineer of the new Holland, who took a large part in the war of liberation. He was responsible for the laws of composition of forces and for the foundations of quantitative hydraulics.

Statics and dynamics: primary and secondary quantities

A full understanding of the movement of massive bodies requires a treatment of forces first in equilibrium, as in *statics*, then out of equilibrium, as in *dynamics*. These were the " Two new Sciences "[4.40] in which Galileo laid the foundations not only of the laws of motion but also of the mathematical theory of the strength of materials, which he based on discussions with master shipwrights.

Galileo stated more clearly than anyone before him that the necessary and intrinsic properties of matter—the only ones in fact that could be dealt with mathematically, and therefore with any certainty—were extension, position, and density. All others, " tastes, smells, colours, in regard to the object in which they appear to reside are nothing more than mere names. They exist only in the sensitive body. . . ." This was not understood by the advocates of the new science as a limitation, but as a programme of reduction of all experiments to the primary qualities of " size, shape, quantity, and motion."

The destruction of ancient cosmology

To win general recognition for his new mathematical–mechanical science Galileo had first to destroy the Ptolemaic system of the heavenly spheres and with it, as he himself saw clearly, the whole Aristotelian philosophy which for nearly 2,000 years had been the foundation not only of the natural but also of the social sciences. He was particularly suited for the task, as he had seen Aristotelian philosophy at its best in Padua. He was no outsider, but was able to refute the master by his own logic in the way in which scholars could not ignore, however much they might disapprove. Implicitly all his work was a

protest against Aristotelians, but his first explicit blast came in 1632 in his polemical book *Dialogue concerning the Two Chief Systems of the World, the Ptolemaic and the Copernican,* which he dedicated to the Pope. Here, not in learned Latin but in Italian for all to read, he mercilessly criticized and ridiculed the officially held views on the most important of subjects. This was the first great manifesto of the new science.

The trial of Galileo

The challenge he put down could not be ignored and led directly to the famous trial. Galileo had made as many enemies in science as in the Church, and with the publication of the *Dialogue* they redoubled their denunciations of him. It is difficult to realize now why such an academic point as the motions of the earth and the planets should have caused such a violent struggle, but in those days far more was seen to be at stake. After centuries of violent disputes, and at the cost of the greatest intellectual effort, the Christian–Aristotelian compromise had been hammered out. Even the doctrinal quarrels of the Reformation had not shaken it. If the challenge in one essential aspect, the constitution of the heavens, was ignored, how much further might not the attack be pressed? Already ardent Copernicans, such as Bruno and Campanella (1568–1639), had drawn conclusions from the new knowledge that threatened the stability of the Church, government, public morals, and property itself (p. 228). Bruno had been burnt, Campanella was imprisoned for years; but with Galileo it was a different matter: he had scientific prestige and powerful friends, his Catholicism was not in doubt, and, except in science, he was not a revolutionary.

The trial was necessarily carried on in terms of the ideas and mode of reasoning of the Church and not those of Galileo, so that the result was a foregone conclusion. But the interesting fact is that the proceedings of the trial were kept secret, most probably because of the danger that their publication would reveal not the severity of the judges but their comparative leniency.[4.102] The Pope and the Curia were more anxious about the possible reactions of the fanatical diehards of the Church than about those of the scientists. Galileo was condemned and forced to make his famous recantation, but he suffered a merely nominal imprisonment in the palace of one of his friends. In his retirement he was able to complete his work

on dynamics and statics and to publish it in the latter years of his life.

Nevertheless, the event of the trial marked an epoch, for it dramatized the conflict between science and religious dogma. Through its effective failure, for the verdict was badly received by nearly all the learned, even in Catholic countries, it gave enormous prestige to the new revolutionary experimental science, especially in countries that had already overthrown the authority of Rome. Galileo's achievement appears as the culmination of the attack on the old cosmology. From then on it was quietly dropped, and practical astronomers used the Copernican–Keplerian model of the solar system. Forty years later the observational laws of Kepler were to be combined with the dynamics of Galileo in Newton's theory of universal gravitation.

Magnetism: Norman and Gilbert

One further physical clue which led to that synthesis was the experimental study of magnetism, known to the world through the publication in 1600 of *De Magnete* by William Gilbert, Queen Elizabeth's physician. The experimental discovery on which it was based, that of the dip of a balanced needle, had already been noticed by Hartmann (1489–1564) in 1544 and studied in detail by Robert Norman (*fl.* 1590), a mariner and compass maker, and one of the first scientists with neither gentle birth nor book-learning. He is fully conscious of his rights as he sets them out in the preface of his *The Newe Attractive* (1581):

> . . . yet I meane God-willing, without derogating from them, or exalting myself, to set down a later experimental truth found in this stone, contrarie to the opinions of all them that have heretofore written thereof. Wherein I mean not to use barely, tedious Conjectures or imaginations: but briefly as I may to passe it over, grounding my Arguements only upon experience, reason and demonstration, which are the grounds of Art. And albeit, it may be said by the learned in the Mathematicalles, as hath beene already written by some, that this is no question or Matter for a Mechanitian or Mariner to meddle with, no more than is the finding of the longitude, for that must bee handled exquisitely by Geometricall demonstration, and Arithmetical Calculation: in which Artes, they would have all Mechanitians and Sea-men to be ignorant, or at

> leaste insufficientlie furnished to performe such a matter, alledging against the latin Proverb of Apelles, *Ne sutor ultra crepidam*. But I doe verily thinke, that notwithstanding the learned in those Sciences, being in their studies amongst their bookes, can imagine greate matters, and set downe their farre fetcht conceits, in faire showe, and with plawsible words wishing that all Mechanitians were such, as for want of utterance, should be forced to deliver unto them their knowledge and conceites, that they might flourish upon them, and applye them at their pleasures: yet there are in this land divers Mechanitians, that in their severall faculties and professions, have the use of those Artes at their fingers endes, and can apply them to their severall purposes, as effectually and more readily, than those that would most condemne them.

I have quoted this at length as a manifesto of the challenge of new craftsmen to the old scholars. It finds an echo in the polemics of Gabriel Harvey (1545–1630), the rope-maker's son, the friend of Spenser who claimed the same rights in literature that were shortly to be vindicated by the glover's son William Shakespeare. Harvey writes: [4.51]

> He that remembreth Humfrey Cole, a Mathematicall Mechanician, Matthew Baker a ship-wright, John Shute an Architect, Robert Norman a Navigator, William Bourne a Gunner, John Hester a Chimist, or any like cunning, and subtile Empirique, (Cole, Baker, Shute, Norman, Bourne, Hester, will be remembered, when greater Clarks shal be forgotten) is a prowd man, if he contemne expert artisans, or any sensible industrious Practitioner, howsoever unlectured in Schooles, or unlettered in Bookes . . . and what profounde Mathematician, like Digges, Hariot, or Dee, esteemeth not the pregnant Mechanician? Let every man in his degree enjoy his due: and let the brave enginer, fine Daedalist, skilful Neptunist, marvelous Vulcanist, and every Mercurial occupationer, that is every Master of his craft, and every Doctour of his mystery, be respected according to the uttermost extent of his publique service, or private industry.

Nevertheless, the scholars still had important tasks to perform. They had to transmit the knowledge of the past to the new craftsmen-scientists till these could all learn to stand on their own feet, and they had, through their connections with rank and wealth, to assure recognition and support for the new

sciences. Gilbert fulfilled both functions admirably. His *De Magnete*, though full of strong invective in Latin as any Norman or Harvey could use in English against the blindness of the old philosophers, was also so well buttressed with scholarship as to compel assent of the whole learned world, though Norman's book must have been of more use to sailors and compass makers.

De Magnete is a great book in itself, and as an exposition of the new scientific attitude. Gilbert did not confine himself to experiments: he drew from them new general ideas. The one that struck most at the imagination of his time was his idea that it was the magnetic virtue of *attraction* that held the planets in their courses. It provided the first physically plausible and completely non-mythical explanation of the ordering of the heavens. It certainly made it easier for Newton in his argument against the physically-minded scientists who could conceive force only by the impulsion of material bodies in contact.

The mechanics of the human body

It was not, however, only in the skies and in the stones that the old views were yielding to the new. At the same time an equally successful attack was being made on the inner universe —the nature of man's body. The Aristotelian world-picture was essentially centred on the earth and man. Man at the centre of the universe was supposed to be in direct contact with all its parts by means of influences and spirits that connected him with the planetary spheres. He was a little world in himself—a microcosm. Its detailed workings had been elaborated by the Greek doctors ending in Galen, whose description of the organs of the human body had become as canonical as Ptolemy's description of the heavens. The new anatomy of the Renaissance, particularly the work of Vesalius, showed that Galen's picture must be wrong; but the alternative explanation could be found only by a totally new approach to the problem, one which combined anatomy with the new Renaissance interest in machinery—bellows, pumps, and valves —and could derive from them a new experimental physiology.

Harvey and the circulation of the blood

This was to be the work of William Harvey (1578–1657), an Englishman of good family, trained in Padua, and so able

to combine the Italian anatomical tradition with the new interest in experimental science that was beginning to find its way into England. What Harvey sought was the mechanical explanation of the movements of the blood in the body. His *Exercitatio Anatomica de Motu Cordis et Sanguinis in Animalibus* published in 1628 is the record of a new kind of anatomy and physiology. No longer is it mere dissection and description, but an active investigation, a piece of hydraulic engineering research carried out by means of practical experiments. Harvey had a difficult case to prove; he had to overcome the disability of being, as it were, a Copernicus, forced to deduce his new system without a Galileo to confirm it by visible evidence. He could prove logically that a circulation must exist, because blood went out of one side of the heart and came back into the other—far more blood than could be currently accommodated in the body itself. But he could not *see* how it got from one side to the other. The fine capillary (hair-like) vessels through which it flowed were to be demonstrated later by Malpighi (1628–94), using the other new optic glass, the *microscope*.

What Harvey established by his close reasoning from experiment had the same revolutionary effect on ancient and Galenic physiology as the discoveries of Galileo and Kepler had on Platonic and Aristotelian astronomy. He showed that the body could be looked at as a hydraulic machine and that the mysterious spirits which were deemed to inhabit it had no place to live in (p. 161). His own views, however, remained more Copernican and Keplerian than Galilean, with a strong sense of the parallelism of the body to the world.[8.27] He writes, for example:

> So the heart is the beginning of life, the Sun of the Microcosm, as proportionably the Sun deserves to be call'd the heart of the world, by whose vertue and pulsation, the blood is mov'd, perfected, made vegetable, and is defended from corruption and mattering; and this familiar household-god doth his duty to the whole body, by nourishing, cherishing, and vegetating, being the foundation of life and author of all.[4.5.56]

Thus he puts the heart in the body in the same royal, central place as the sun in the universe. Harvey's beautiful demonstration of the mechanics of circulation gave great weight to the idea that an organism was a machine, though it turned out

later that it was one far more complicated than the men of the sixteenth and seventeenth centuries imagined.

Harvey's discovery had, however, very little immediate effect in medicine, apart from justifying methods to prevent people from bleeding to death, already practised by field surgeons like Paré. It was, however, absolutely necessary as a foundation for any rational physiology. The picture of the organism, as it grew up from Harvey's work, is that of a set of organs, what might be called "irrigated fields," provided with a circulation which keeps every part in communion with the rest in a nutritive and chemical way.

Chemistry

This understanding was to be delayed, for the chemical advances of the century from 1540 to 1640 had not been startling. The only man of first-class mind to have occupied himself with it was van Helmont (1577–1644), a nobleman trained in medicine and a follower of Paracelsus, whose mystical views he approved though he had no need for his bombast. His chemical ideas hark right back to the Ionians, believing the only elements to be air and water. But this was not so much a philosophic hypothesis as an experimental conclusion, for he grew a willow tree from a seed in a pot to which water only had been added. He was also the first to name and study gas—or chaos—pointing the way to the triumphs of later chemistry. For the rest, chemistry pursued its slow and steady course of widening its basis of experience, improving the accuracy of its measurements, and increasing the scale of its operations, particularly in the distillation of spirits.

7.6.—*THE NEW PHILOSOPHY*

The two great and hard-won discoveries of the rotation of the planets and of the circulation of the blood were both securely established by 1642, the year Galileo died and Newton was born. The first intellectual object of the scientific revolution had been achieved: the classical world-picture had been destroyed, though only the bare outlines of a new one had been put in its place. In doing so new means for understanding and conquering Nature had been found, but little had as yet emerged that could be claimed to be of general practical use. The telescope itself was a technical rather than a scientific invention. Before

the effects of the revolution in thought could make themselves felt in practice, it was necessary that the possibilities the new science offered should be brought home not only to the learned but to the new class of enterprising people that were making their own political revolution—merchants, navigators, manufacturers, statesmen, and the early and progressive capitalists. Galileo had started to do this, but he was living in a country that had already lost its *élan* and that was rapidly being frozen into reaction by the counter-Reformation.

The prophets: Bacon and Descartes

Two men from the less cultured but far more active northern countries were to take on the task—Bacon and Descartes. These two major figures stood at the turning point between medieval and modern science. Both were essentially prophets and publicists, men who had seen a vision of the possibility of knowledge and were making it their business to show it to the world. Both were universal in scope, though their approaches to knowledge were very different. Temperamentally, too, it would be difficult to find two more different people than the shrewd, self-seeking, and afterwards rather pompous lawyer, always at the centre of public affairs, and the intensely introspective, solitary ex-soldier of fortune. Each too is characteristic of the nature of the scientific revolution in his own country.

Bacon emphasized the essentially practical side of the new movement, its applications to the improvement of the arts, its usefulness in bringing about a more common-sense appreciation of the world around them. Living as he did in the courts of Elizabethan and Jacobean England, he found that his difficulties arose not so much from the existence of rigid systems of thought as from the need to lay solid institutional foundations for a new and generally acceptable philosophy. This was put forward not only to replace the older views, but also to put in order the chaos of speculations that the Reformation in England had produced. Descartes, on the other hand, had to fight against a medieval system of thought entrenched in the official universities of France, and only succeeded by using a logic that was clearer and intellectually more compelling than theirs.

The Novum Organum and the Discours de la Méthode

Both thinkers were preoccupied with methods, though their ideas of scientific method were very different. Bacon's was

that of collecting materials, carrying out experiments on a large scale, and finding the results from a sheer mass of evidence—an essentially *inductive* method. Descartes, on the other hand, believed in the rapier thrust of pure intuition. He held that with clarity of thought it should be possible to discover everything rationally knowable, experiment coming in essentially as an auxiliary to *deductive* thought. The major difference, however, was that while Descartes used his science to construct a *system* of the world, a system which, though now almost forgotten, was able in its time completely to supersede that of the medieval schoolmen, Bacon put forward no system of his own but was content to propose an *organization* to act as a collective builder of new systems. His function as he saw it was only to provide the builders with the new tool—the logic of the *Novum Organum*—with which to do it.

In this sense they were strictly complementary. Bacon's concept of organization led directly to the formation of the first effective scientific society, the Royal Society. Descartes' system, by breaking definitely with the past, put up a set of concepts which could be the basis of argument about the material world in a strictly quantitative and geometric manner.

The thoughts of both philosophers were, nevertheless, inevitably deeply tinged with medieval ideas, though each in a different way. Francis Bacon belonged to the tradition of the encyclopædists, of his namesake Roger Bacon and of Vincent of Beauvais (p. 226), or, tracing farther back, of Pliny and Aristotle himself. He was, first and foremost, a naturalist in interest and had no knowledge of or sympathy with the new mathematical philosophy. His method was largely negative, based on the avoidance of the "idols" or false lures of ideas that had led the old philosophers astray. His imaginary House of Solomon in his *New Atlantis* [4.19] was a kind of universal laboratory, an idealization of the actual observatory of Tycho Brahe at Uraniborg. It was in turn to be the inspiration of later scientific institutes. Though a believer in experiments, Bacon was not an experimenter himself, and he never fully understood the process of abstraction and reduction needed to extract truth from complex situations which Galileo was already using so magnificently. He thought that systematic, common experience, purged of the pernicious ideas of the Ancients, would suffice for knowledge. His scientific beliefs were not original

but drawn from reading, particularly of Telesius, whom he criticized but called " the first of the moderns."

Telesius (1509–88), an Italian scholar, was the first to break absolutely with Aristotle by setting up a rival system. His great contribution was the abandoning of Aristotle's formal and final causes and the retention of only material and efficient causes (p. 144). In this he was followed by all later science. His own views recall those of Anaximenes. His universe worked by means of the inner powers of heat and cold. This was an anticipation of the doctrine of energy and included some idea of conservation, but was not much more advanced quantitatively than the Yang and the Yin of Chinese philosophy (p. 121).

From the very beginning of his career Bacon set out to preach the doctrine that " The true and lawful end of the sciences is that human life be enriched by new discoveries and powers."

He saw himself not so much as a scientist and inventor, but as an inspirer of science and invention: " I have only taken upon me to ring a bell to call other wits together." In his admirable study of Francis Bacon, Professor Farrington quotes: [4.37]

> Nowe among all the benefits that could be conferred upon mankind, I found none so great as the discovery of new arts, endowments, and commodities for the bettering of man's life. For I saw that among the rude people in the primitive times that authors of inventions and discoveries were consecrated and numbered among the gods. And it was plain that the good effects wrought by founders of cities, law-givers, fathers of the people, extirpers of tyrants, and heroes of that class, extend but over narrow spaces and last but for short times; whereas the work of the Inventor, though a thing of less pomp and show, is felt everywhere and lasts for ever.
>
> But above all, if a man could succeed, not in striking out some particular invention, however useful, but in kindling a light in Nature—a light which should in its very rising touch and illuminate all the border-regions that confine upon the circle of our present knowledge; and so spreading further and further should presently disclose and bring into sight all that is most hidden and secret in the world—that man (I thought) would be the benefactor indeed of the human race—the propagator of man's empire over the universe, the champion of liberty, the conqueror and subduer of necessities.*

Bacon was taken to be, and rightly, the first great man who had given a new direction to science and who had linked it definitely once more to the progress of material industry.

With his empirical bent Bacon was inevitably an opponent of all predetermined systems in Nature; he believed that, given a well-organized and well-equipped body of research workers, the weight of facts would ultimately lead to truth. Descartes' method, on the other hand, was a more direct successor of that of the schools, with this absolute difference: that it was not *their* system that he wanted to establish but *his own*. In this he exhibited that individual arrogance which was one of the great liberating features of the Renaissance, the same arrogance that expressed itself in the great navigators, in the *conquistadores*, in all the defiances of authority that characterized the end of the feudal period and the beginning of one of individual enterprise.[4.4]

Unconsciously, Descartes' system incorporated very much of the system which he wished to destroy. There was the same insistence on deductive logic and self-evident propositions, but starting with these he used the *mathematics*, of which he was a master, to arrive at conclusions far beyond the reach of his medieval or even of his classical predecessors. His major mathematical contribution was the use of co-ordinate geometry, by which a curve could be completely represented by an equation relating the values of the co-ordinates of its points referred to fixed axes. This was more than the mapping of geometry. It broke down the old distinction between the Greek science of the continuum—*geometry*—and the Babylonian–Indian–Arabic calculus of numbers—*algebra*. Henceforth their two powers would be joined to attack problems never before attempted.

In his attack on the old philosophy Descartes was as canny as he was courageous. He had no desire to enter into a head-on conflict with organized religion, a conflict that had led to the condemnation and burning of Bruno in Catholic Rome and that of Servetus in Calvinist Geneva. He was prepared to be accommodating, and he hit on an ingenious method of doing so which was to make science possible for several centuries at a cost which we are only now beginning to feel.

Primary and secondary qualities

Descartes formulated, more precisely than anyone before him, the division of the universe as we see it, into a part which is

physical and one which is moral. Other philosophers, going back to the Arabs and the Scotists in the Middle Ages including Roger Bacon, as well as Francis Bacon himself, had made reservation of the knowledge that only came by faith or revelation (p. 221), but this pious reservation was *ad hoc* and was open to the objection that it implied that God was irrational. With Descartes this separation became an integral and rational part of philosophy. It was a logical consequence of his reduction of sensory experience first to mechanics and then to geometry. As with Galileo, extension and movement were the only physical realities that he recognized as "primary"; other aspects of existence, such as colours, tastes, smells, were referred to as "secondary" qualities. Beyond these stretched a region even more unapproachable by physics, the region of the passions, of will, love, and faith. Science, according to Descartes, concerned itself mainly with the first set—the measurables, the bases of physics; and to a lesser extent with the second; but not at all with the third, as they lay in the realm of revelation.[4.31] To Descartes, animals, including men, were in themselves merely machines. Obviously there must be some connection between the purely mechanical man, operating his limbs according to physical principles, and the rational spirit and will dwelling within him. Descartes made the naïve, but apparently quite serious, suggestion that that connection could be through the small gland at the top of the skull—the pineal body—the relic of a pair of eyes in our reptilian ancestors, but having now no apparent function and therefore quite reasonably, if not the seat, at least the point of entry of the rational soul.

The separation of religion and science

The effect of Descartes' division ever since was to enable scientists to carry on their work free from religious interferences so long as they did not trespass into the religious sphere. This was, of course, very difficult to avoid or refrain from, but nevertheless it had the effect of producing the type of pure scientist who kept out of fields where he was likely to be involved in controversies of a religious or political kind. To a certain extent Descartes himself must have done this, because the story goes that when he had ready his *System of the World* he heard the news of the trial of Galileo and realized that it simply would not do as it was. The Church was clearly determined that the Aristotelian–Thomist system was necessary to secure

the truths of the Faith and was not going to tolerate any other system that might put them in question. Descartes consequently set himself to the task of showing that his systems could prove the existence of God quite as well as, if not better than, the older philosophies. From his famous first deduction *Je pense donc je suis*—" I think, therefore I am "—he drew the conclusion that as all men can conceive something more perfect than themselves, a perfect being must exist. Descartes' system was so carefully guarded against theological attack that, in spite of protests from the universities, it was accepted in that most Catholic country, France, within his own lifetime and for a century after his death.

Descartes' system was, however, in spite of its wealth of mathematical and observational content, essentially a magnificent poem or myth of what the new science might be. That was at the same time its attraction and its danger. It was a mixture of conclusions soundly based on experiment with those deduced from first principles chosen, according to Descartes' celebrated *Method*, only on account of their *clarity*. The pursuit of that clarity has been the ornament and the limitation of French science ever since. Where in the state of knowledge it was admissible, as in eighteenth-century dynamics and chemistry and in nineteenth-century bacteriology, it could be used to put in order whole fields of genuine but chaotic knowledge. Elsewhere it tended to degenerate into arid commonplaces and false simplifications.

To a certain extent Descartes himself recognized the limitation of a one-man enterprise in philosophy, and realized that the proper establishment of the system of the world would require the co-operation of many minds. In the *Discours de la Méthode*, he says, speaking of experiments:

> I see also that there are so many of them that neither my hands nor my wealth, even if I had a thousandfold what I have, would serve me for this end. . . . What I had to show by my treatise was the utility that the public can gain from it and that I should oblige all those who desire the good of mankind, that is to say all those who are really virtuous and not only pretend to be, to communicate to me their own results and to help me in the researches that still have to be made.

In another place he says, to justify the publication of his own conclusions:

> They showed me that it is possible to arrive at knowledge very useful to life: and that instead of this speculative philosophy that is taught in the schools one can find a practical philosophy by which *knowing the force and action of fire, water, air, the stars, the heavens, and all other bodies that surround us as distinctly as we know the different trades of our craftsmen, we could employ them in the same way to all uses for which they are appropriate and thus become the masters and possessors of Nature.* This is not only desirable for the invention of an infinity of artifices which would enable us to enjoy without trouble all the fruits of the earth—but principally in the preservation of Health.

Thus in his ultimate objective Descartes did not differ much from Bacon, for whom he had, in any case, the greatest admiration. Bacon and Descartes between them raised the status of experimental science to an esteem in polite circles comparable to that of literature. From their time on the new natural philosophy, and not that of the schools, was the centre of interest and discussion. Indeed, after another 200 years or so it had just about fought its way into the universities of England.

The time was now ripe for a great expansion of this natural science and its first fruits. In the next period from 1650 to 1690 the "Great Instauration"—or as we would say Reconstruction—of which Bacon dreamed was at last to take place.

> I entrust men to believe that it is not an opinion to be held but a work to be done: and to be well assured that I am not labouring to lay the foundation of any sect or doctrine, but of human utility and power.

7.7—*THE THIRD PHASE: SCIENCE COMES OF AGE 1650–90*

The third and definitive phase in the establishment of modern science was reached in the latter half of the seventeenth century. Intellectually, as we have seen, the ground had been prepared for it by the overthrow of the feudal-classical theories in the previous hundred years. Though this made further advance and consolidation of science possible, it was not the only, nor the main, cause of the outburst of activity which, in less than fifty years, virtually created modern science in most of its fields. This intense growth was more concentrated than at any time

before or since. The principal foci were London and Paris, for the active scientists of Italy and Holland found no such centres of expression in their own countries, while those of central and eastern Europe had not yet come into action.

The condition which made this rapid growth possible and favoured its concentration was first and foremost the establishment in Britain and France of stable governments in which the upper bourgeoisie had a dominating, or at least an important, part. In Britain the Civil War had brought about a real revolution, in which the richer merchants with the help of the townsmen and small landowners had won power from the king and the landed nobility. But these groups, after their triumph, soon quarrelled. The small men had a distressing tendency to democracy and economic equality,[6.180] and as soon as Cromwell was out of the way the merchant interest arranged a compromise with the landlords in which King Charles II came in as the first constitutional monarch. The merchants still dominated the economy, but a new class of manufacturers were making their first appearance, drawn partly from the ranks of the merchants, partly from that of the skilled craftsmen. The great increase of manufacture and trade that followed the end of the Civil War, together with the new possibilities of navigation, kept mechanical invention at a premium. The time and place were in every way most propitious for the growth of science.

Holland, though immensely rich, was by the middle of the century past her prime. Sixty years had passed since the revolution which had ended the rule of Spain. The popular support that had secured the independence of the country had been largely dissipated, and the government was in the hands of a combination of wealthy merchants and landlords. Soon, exhausted by commercial wars and without adequate manufactures, Holland was to prove too weak to maintain her leading place. Already by the end of the century some of the most able Dutchmen took service abroad, particularly in the development of Britain under William of Orange, while Holland's greatest scientist, Christian Huygens, did most of his work in Paris as a member of the French Academy.

In France, on the other hand, the Revolution was still in the future. The strength of feudalism and of the Church had been shown in the crushing of the Huguenots; but this was a slow process and was only fully effected by the revocation of the

Edict of Nantes in 1685. Nor could this vigorous and expanding country, then by far the largest and richest in Europe, stand aside from the general economic development. A compromise was patched up by which the nobles bartered part of their power for tax exemption, pensions, and pageants at Versailles. The executive power was centred on the king, but his State machine was bourgeois throughout. It was largely run by intelligent lawyers, the *Noblesse de Robe*, from which many scientists were to come. Actually, the compromise only worked tolerably well in the early part of Louis XIV's personal reign (1661–83) under the direction of the business-like Colbert, and this coincided exactly with the great period of science.

The other countries of Europe played minor parts on the scientific stage: Germany and Austria had only begun to recover from the Thirty Years War (1618–48); the Inquisition neutralized Spain and Portugal almost completely; while in Italy the heirs of Galileo fought a gallant rearguard action against the forces of clericalism.[4.90; 4.102] Sweden, Poland, and Russia were still largely raw-material countries in the throes of a newly imposed serfdom and, though militarily strong, were only beginning to contribute to science at this stage.

Le Grand Siècle

After the great religious and political disturbances of the previous hundred years the latter half of the seventeenth century was a period of relative calm and active prosperity. Plagues and wars were constant but had surprisingly little effect on the work of the scientists. Nor did national rivalry seriously interfere as yet with their freedom of movement or communication. It was an age of conscious building of civilization—Le Grand Siècle—and the scientists were recognized and honoured as part of one common world of letters. The governments and the ruling classes of all the leading countries had certain common interests in trade and navigation, and also in improvements in manufactures and agriculture. These interests were to furnish the motive power for the culminating achievements of this third phase of the Scientific Revolution, the first in which an organized and conscious effort was made to use science for practical ends.

This was the *fruit* which, thirty years before, Bacon had urged men to cultivate; and Bacon's methods, both those of experiment and of organization of research, were used to gather it.

The men who were to do so were characteristic of their age and nations. In the place of the courtiers and university professors of the first two phases, depending for their livings on the favour of princes, the *virtuosi* of the mid-seventeenth century were men of independent means, mostly merchants, middling landowners, and successful followers of the liberal professions—doctors, lawyers, and not a few parsons. They might seek royal patronage but they could count on little royal money for science; King Charles II never paid a penny to his Royal Society and never even managed to find time to visit it. The *virtuosi* had to finance science out of their own pockets. But these pockets were ample and were being rapidly filled by the great increase in trade, whose benefits now flowed into the very countries where science flourished. Some were even able to take on other scientists about the work. The Hon Robert Boyle employed Hooke, a poor curate's son, just as Christian Huygens, lord of Zulichem in Holland, employed Denis Papin of Blois.

These men were competent and interested enough to carry out scientific research on their own; but as they became more numerous they tended to gravitate naturally together for discussion and interchange of knowledge, made all the easier by the commercial and levelling tendencies of the time. They went further: inspired by the propaganda of Bacon they began to think of a positive organization deliberately aimed at winning the secrets of Nature by a co-operative effort.

The foundation of scientific societies

This third phase accordingly was the period of the formation of the first well-established scientific societies, the Royal Society of London and the French Royal Academy, which set themselves the task of concentrating on the central technical problems of the time, those of *pumping* and *hydraulics*, of *gunnery* and of *navigation*, while almost ostentatiously avoiding general philosophical discussions. It was particularly the navigational problems that furnished the stimulus to the advancement of science, because it was through the attack on these problems that the two elements of earlier science—mechanics and astronomy—were brought together in the great synthesis of Newton. In the latter part of this chapter I will try to trace some of the threads of experiment and argument that led to this synthesis. More important practical results were, however, to

come from the study of the pump, which was to lead first to the discovery of the *vacuum*, then to that of the laws of gases—from which arose the steam-engine, as well as the pneumatic revolution of chemistry in the next century.

The establishment of science as a fully recognized factor in culture was definitive from the moment that scientific societies were formed. The idea of a scientific society was, as we have seen, a very old one. It found expression in the original Academy (p. 139), in the Lyceum (p. 141), and in the Museum of Alexandria (p. 152). Both Muslim and Christian universities were something of the same kind in their early stages, but by the seventeenth century it was evident that these could not fill the new needs. Something different was wanted and in due course appeared, partly in response to the inspiration of prophets of the new age like Francis Bacon, but even more as a formal recognition of spontaneous gatherings of men interested in science.

Among the prophets, John Amos Comenius (1592–1670), the last bishop of the Moravian Church, was an outstanding figure.[4.72] Approaching science as a part of universal education, to which he had devoted most of his life, he planned a " Pansophic College " where the new experimental philosophy would be practised and taught. Driven out of Bohemia by the Thirty Years War he lived a wandering life, and was sought after by forward-looking governments because of his successful educational methods. It was beginning to be recognized by the statesmen of the new national States that an educated laity was needed to run the administration. In 1641 Comenius came, at the invitation of Parliament, to England, where he hoped to found his college. Though, owing to the difficulties of the time, he failed in this, his influence played some part in bringing the Royal Society into existence.[4.98]

Actually the earliest of the scientific societies were the Accademia de Lincei at Rome (1600–30) and that of the Cimento at Florence (1651–67).[4.8] These, though they acted as models for societies elsewhere, arrived too late on the Italian scene to halt the factors inimical to science which soon led to their extinction. The Royal Society of London (1662) and the Académie Royale des Sciences in France (1666) were more fortunate. All arose originally from early informal gatherings of friends interested in the new sciences.

French scientists, among them Gassendi, who reintroduced

the atomic theory, had been meeting at the house of a wealthy lawyer, Pieresc, at Aix-en-Provence as early as 1620.[4.25] The real centre of French science was, however, until his death in 1648 the cell of the minorite friar, Mersenne, himself no mean scientist. He was an indefatigable correspondent, acting as a kind of general post office for all scientists in Europe from Galileo to Hobbes.[4.69] Later, meetings were held in the house of another lawyer, Montmor, out of which the Royal Academy was ultimately to be formed.

Another promoter of a rather different type was Renaudot (*d.* 1679), a lively and combative doctor who, much to the horror of the faculty in Paris, set up a clinic giving free treatment to the poor. He combined this establishment with a lecture room for scientific meetings, a publishing house, and an employment agency, which largely paid for the whole outfit. With the death of his protector Cardinal Mazarin in 1661, his enemies succeeded in shutting it down and putting an end to popular science in France for more than a hundred years.

In England the signal for the gathering of the new experimental scientists was the end of the Civil War in 1645. Most of them were Parliamentarian in sympathy, some Puritans, but had little to do with the actual fighting. The leading spirit of the group was John Wilkins, a clergyman of some adaptability in politics, marrying Cromwell's sister and ending as Bishop of Chester, but an unswerving supporter of the new philosophy. With him were associated the mathematician Dr Wallis, Dr Theodore Haak, a German refugee who was first to suggest the weekly meetings, and a number of doctors. After some preliminary meetings in London they settled down in Oxford in 1646. That loyal university had just been reformed by a Parliamentary Commission, and the empty chairs and headships of houses were filled with the new members of the "Invisible College." Until the Restoration in 1660 Oxford was to be, anomalously and somewhat unwillingly, the centre of the attack on Aristotle, who had been so revered there before and since. In Oxford the band was strengthened by the adherence of three young men of promise, the Hon Robert Boyle, Sir William Petty, and Dr Christopher Wren, and also, though in a humbler capacity, Robert Hooke, the man who was to do most to make the Royal Society a success. As Thomas Sprat, one of the group, the future bishop of Rochester and historian of the society,[4.93] wrote of those times:

Their first purpose was no more, then onely the satisfaction of breathing a freer air, and of conversing in quiet one with another, without being ingag'd in the passions, and madness of that dismal Age. And from the Institution of that *Assembly*, it had been enough, if no other advantage had come, but this: That by this means there was a race of young Men provided, against the next Age, whose minds receiving from them, their first Impressions of *sober* and *generous knowledge*, were invincibly arm'd against all the inchantments of *Enthusiasm* . . .

For such a candid, and unpassionate company, as that was, and for such a gloomy season, what could have been a fitter Subject to pitch upon, then *Natural Philosophy*?

. . . *that* never separates us into mortal Factions; that gives us room to differ, without animosity; and permits us, to raise contrary imaginations upon it, without any danger of a *Civil War*.

Their *meetings* were as frequent, as their affairs permitted: their proceedings rather by action, then discourse; chiefly attending some particular Trials, in *Chymistry*, or *Mechanicks*: they had no Rules nor Method fix'd: their intention was more, to communicate to each other, their discoveries, which they could make in so narrow a compass, than an united, constant, or regular inquisition.

At first these amateur scientists merely met, discussed, showed each other experiments, and wrote letters to their absent friends or to their colleagues in other countries. The business of scientific communication and publication originated in these at first purely informal and then more regular letter-writings. Later, the need for a definite establishment was felt by the scientists both in England and France because, as they continued their work, they realized that it was likely to have considerable practical importance, and to carry it out they would have to have more money or more recognition.

The procedures differed according to the character of the economies of the two countries. In France, with its rigidly centralized government, it was natural that the establishment should be not only royally instituted but also royally paid. Colbert was setting up national industries in France, and it was accordingly not difficult to persuade him to found the Academy of Science to balance Mazarin's Academies of Literature and Fine Art. But then, ornament and show, just as much as commerce, were necessary to the glory of the king-

dom of *le Roi Soleil.* The industries favoured by Colbert were those of silk-weaving at Lyons, pottery at Sèvres, and the Gobelin tapestries in Paris, all considered of importance comparable to the shipbuilding for the French Navy.[4.7]

In Restoration England, on the other hand, with its relics of republican independence and where the real wealth of the country was in the hands of the landed aristocracy and the merchants, royal patronage was all that was required. The Fellows of the new Royal Society paid for their own scientific investigations. The charge was one shilling per member per week. It was extremely difficult to collect and was hardly sufficient to pay the secretary and the curator, who " shall be well skilled in Philosophical, and Mathematical Learning, well vers'd in Observations, Inquiries, and Experiments of Nature and art," and was obliged to " furnish the Society every day they meete, with three or four considerable experiments, expecting no recompense till the Society gett a stock enabling them to give it." [4.11]

The necessary consequence of official recognition of the societies was general conformity of ideas and avoidance of controversial issues in politics and religion. In France the Church grudgingly withdrew its insistence on Aristotelianism and accepted the compromise proposed by Descartes (p. 307). In Britain the same division of fields of interests came about in a different way. It arose from the troubles of the Great Rebellion in the middle of the seventeenth century and the desire of the early scientists to avoid the endless theological–political disputes that occupied most intellectuals in those times. In the draft preamble to the Statutes of the Royal Society written by Hooke in 1663, it was laid down that:

> The business of the Royal Society is: To improve the knowledge of naturall things, and all useful Arts, Manufactures, Mechanick practices, Engynes and Inventions by Experiment—(not meddling with Divinity, Metaphysics, Morals, Politics, Grammar, Rhetorick, or Logicks).[4.11]

Promise and performance: early failures and later successes

It is interesting to note that both in France and in England the full activity of the societies, as such, was limited to a relatively short period; by 1690 both were in a serious state of decay and their revival in the eighteenth century was practically a new foundation. Their coming into existence and the

general support and the interest they aroused in society at large were an indication that science was at that time felt to be exciting, interesting, and might be profitable. It was this last point that was to give rise to serious difficulties. Francis Bacon, like Roger Bacon four centuries earlier, had clearly grasped the idea that the understanding of Nature was the only means of controlling it to the profit of man. But there is a great deal of difference between an idea and an achievement. In fact, it was in one realm alone, though a very important one—that of astronomy and navigation—that the new science, which was practically confined to mathematics and physics, was able to be of real use. Sir Antony Deane did manage in 1666 to find the draught of a ship before it was launched, but this did not notably effect shipbuilding practice. The early Royal Society promised far more than it could perform, and there was some justification, in the short run, for the ridicule with which it was met by the non-scientific intelligentsia, of which the most famous example is the satire by Swift in *Gulliver's Travels*.

In the long run, however, the effect was to be very different. By stimulating the "naturalist's insight into trades" (p. 323) it was enabled to lay the foundations of that rational evaluation and reconstruction of the traditional arts and manufactures that was to become the Industrial Revolution of the next century. Indeed its work was to lead directly to the central feature of that revolution—the steam-engine which has every right to be called a *philosophical engine*. It is the fruit not of the work of one or other isolated inventor, but of groups of scientists in the Accademia del Cimento, the Royal Society, and the French Academy (pp. 414 f.).

Science becomes an institution

The foundation of the early scientific societies had another and more permanent effect: it made science into an institution, an institution with the insignia, the solemnity, and with, unfortunately, a certain amount of the pomp and pedantry of the older institutions of law and medicine. These societies became in effect a jury for science, a jury sufficiently authoritative to exclude many of the charlatans and madmen whom the general public found it so difficult to distinguish from genuine scientists; but also, unfortunately, able to exclude, for a time at least, many revolutionary ideas from official science itself (p. 422). The range of interest of the associated scientists of the latter

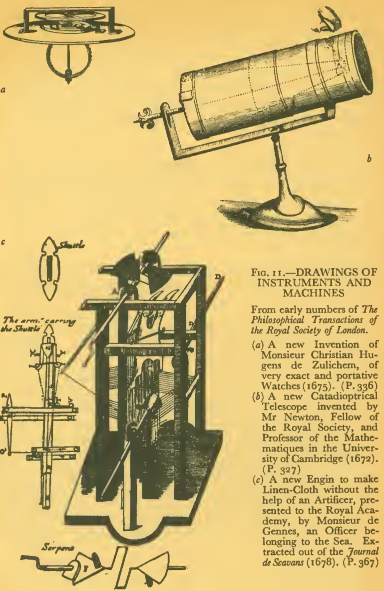


FIG. 11.—DRAWINGS OF INSTRUMENTS AND MACHINES

From early numbers of *The Philosophical Transactions of the Royal Society of London.*

(*a*) A new Invention of Monsieur Christian Hugens de Zulichem, of very exact and portative Watches (1675). (P. 336)
(*b*) A new Catadioptrical Telescope invented by Mr Newton, Fellow of the Royal Society, and Professor of the Mathematiques in the University of Cambridge (1672). (P. 327)
(*c*) A new Engin to make Linen-Cloth without the help of an Artificer, presented to the Royal Academy, by Monsieur de Gennes, an Officer belonging to the Sea. Extracted out of the *Journal de Scavans* (1678). (P. 367)

seventeenth century, as their *Philosophical Transactions* show, covered almost every aspect of Nature and of practical life from the distances of the stars to the animalcules in pepper water, from the art of dyeing to the bills of mortality.[4.93]

The first manifesto of the newly organized science was the *History of the Royal Society* written in 1667, when it was only five years old, by Bishop Sprat. Inevitably it is more than a history, rather a programme and a defence of experimental philosophy. After denouncing varieties of dogmatic philosophers he approves:

> The *Third* sort of *new Philosophers*, have been those, who have not onely disagreed from the *Antients*, but have also propos'd to themselves the right course of slow, and sure *Experimenting*: and have prosecuted it as far, as the shortness of their own Lives, or the multiplicity of their other affairs, or the narrowness of their Fortunes, have given them leave.

He defends the inclusion in the Society of men of all ranks and occupations, and from all countries, and then touches on the essential *raison d'être*, which is:

> the temper of *the age wherein we live*. For now the Genius of *Experimenting* is so much dispers'd that even in this *Nation*, if there were one, or two more such *Assemblies* settled; there could not be wanting able men enough, to carry them on. All places and corners are now busie, and warm about this Work: and we find many Noble Rarities to be every day given in, not onely by the hands of Learned and profess'd Philosophers; but from the Shops of *Mechaniks*; from the Voyages of *Merchants*; from the Ploughs of *Husbandmen*; from the Sports, the Fishponds, the Parks, the Gardens of *Gentlemen*; the doubt therefore will onely touch *future Ages*. And even for them too, we may securely promise; that they will not, for a long time, be barren of a Race of inquisitive minds, when the way is now so plainly trac'd out before them; when they should have tasted of these first Fruits, and have been excited by this Example.

He concludes his discussion of the experiments and instruments of the Society by commenting on " the manner of their Discourse " and the need to remove " the luxury and redundance of speech." For this reason they rigorously:

> . . . reject all the amplifications, digressions, and swellings of style: to return back to the primitive purity, and shortness, when men deliver'd so many *things*, almost in an equal number of *words*. They have exacted from all their members, a close, naked natural way of speaking; positive expressions, clear senses; a native easiness: bringing all things as near the Mathematical plainness, as they can: and preferring the language of Artizans, Countrymen, and Merchants, before that, of Wits, or Scholars.

The fact remains that the style of the English language was drastically simplified in the latter seventeenth century.[4.61; 4.62] It is a curious commentary on this that 100 years later Samuel Johnson wrote of Sprat:

> This is one of the few books which selection of sentiment and elegance of diction have been able to preserve, though written upon a subject flux and transitory. The History of the Royal Society is now read, not with the wish to know what they were then doing, but how their transactions are exhibited by Sprat.[4.60]

Centres of interest in technique

It appeared at first that anything and everything could be improved by philosophical inquiry. Nevertheless, certain fields of interest drew the special attention of the *virtuosi*. They were those where the themes of the new philosophy met the most clearly felt needs of expanding trade and manufacture. Foremost among these was the refinement of astronomy as an essential need of ocean navigation, particularly in solving the problem of the longitude. This was indissolubly linked with the problem of the true constitution and working of the solar system, by now accepted but not physically explained. Further, it was astronomy that provided the best field for the new *mathematical* explanation of the universe. The solution finally arrived at by Newton was taken to be, and rightly so, the major triumph of the new science.

But this contemporary interest should not be allowed to overshadow other developments which were in the long run to prove at least as important. One of these was *optics* and the *theory of light*, closely linked by the telescope to astronomy, and by the microscope to biology. Another was *pneumatics*, where the techniques developed in connection with the vacuum were ultimately to have such enormous industrial importance. The

question of the *vacuum* was also the centre of a philosophic controversy going back to the Greeks. The new experimental proofs of its existence helped to revive the *atomic* hypothesis of Democritus. The revived atomic or corpuscular theory provided a first clue to rational and quantitative explanations in the field of chemistry, which had hitherto been one of technical recipes and mythical explanations. Chemistry, in turn, was linked with the beginnings of *physiology*. Questions on the nature of the blood, the function of the lungs, the action of nerves and muscles, and the processes of digestion, were all discussed and experimented on in the spirit of the new materialist philosophy. This range of subjects was not beyond the reach of individual men of the time, and indeed it is best illustrated in their lives and works. Outstanding among them were Robert Boyle and his one-time assistant Robert Hooke.

Robert Boyle

The Hon Robert Boyle was born at Lismore in 1627, the seventh son and thirteenth child of Richard Boyle, first Earl of Cork, a ferocious and successful land-grabber of Elizabethan times.[4.67] Young Robert spent his most impressionable years in the Puritan atmosphere of Geneva, where he underwent a religious conversion, like his contemporaries Pascal and Steno. Unlike Pascal, however, this did not turn him against science but made him strive to use it in the support of revelation. Partly for this reason and partly because he was a lifelong invalid, he led an ascetic life, took no sides in the Civil War, and devoted himself and his considerable wealth to the pursuit of the new experimental philosophy. He worked with the "Invisible College" in Oxford and was one of the first promoters of the Royal Society, of which he was offered the presidency in 1680 but declined on account of a scruple about the oath. Boyle was, indeed, the central figure of the early days of the Royal Society, as Newton was of its prime. He wrote profusely on religious and scientific subjects. His most famous works, apart from that on the *Spring of Air*, were the *Seraphick Lover*, *The Skeptical Chymist*, and the *Unsuccessfulness of Experiments*. His early interest in the atomic theory led him to his epoch-making work on the vacuum and gas laws. After that he was not so successful, partly because he lacked adequate mathematical and experimental skill, but mostly because he attempted to explain problems in chemistry by mechanical

theories which could not be applied to them and before enough facts had been accumulated to solve them by any other means. His interests ranged further still into physiology and medicine, where there was still less hope of solid achievement. Nevertheless he infected others with his interests and enthusiasms and much of the success of science in the next century was due to his inspiration. In Boyle we can see the pietistic and philanthropic aspects of the new science. He combined the desire to show the glory of God revealed in His works with that of helping his fellow men, and he actually joined the boards of the Bermuda and East India Companies to further his schemes for converting the heathen. Nevertheless in the achievements of these ends he was, unlike the medieval pietists, intensely practical. In his pamphlet *That the Goods of Mankind May be Increased by the Naturalist's Insight into Trades* [4.24] he wrote:

> . . . I shall conclude this, by observing to you, that as you are, I hope, satisfied, that experimental philosophy may not only itself be advanced by an inspection into trades, but may advance them too; so the happy influence it may have on them is none of the least ways, by which the naturalist may make it useful to promote the empire of man. For that the due management of divers trades is manifestly of concern to the publick, may appear by those many of our English statute laws yet in force, for the regulating of the trades of tanners, brick burners, and divers other mechanical professions, in which the lawgivers have not scorned to descend to set down very particular rules and instructions.

Robert Hooke

In many ways Boyle contrasts with his first assistant and lifelong friend, Robert Hooke. If one was a nobleman condescending to science, the other was a poor man who had to make his living out of science while he pursued it. The son of a clergyman in the Isle of Wight, Hooke managed to secure a servitorship at Oriel College at the time when Boyle had come to Oxford. He early attached himself to him and, in fact, probably made all his apparatus and carried out most of his experiments on the vacuum and gases. Boyle certainly did not shine as an experimenter after Hooke left him. Hooke was made curator of experiments of the Royal Society when it was founded, and as well as carrying out his heavy duties managed

to supplement his meagre and irregular salary by being largely responsible for the plans of the new City of London after the Great Fire of 1666.

If he had been in a more secure social position and had not suffered from his ugliness and chronic ill health, he would not have been the difficult, suspicious, and cantankerous person he was, and his quite decisive role in the history of science would have been fully recognized. If Boyle was the spirit behind the Royal Society, Hooke provided it with eyes and hands. He was the greatest experimental physicist before Faraday, and, like him, lacked the mathematical ability of Newton and Maxwell. His interests ranged over the whole of mechanics, physics, chemistry, and biology. He studied elasticity and discovered what is known as Hooke's law, the shortest in physics: *ut tensio sic vis* (extension is proportional to force); he invented the balance wheel, the use of which made possible accurate watches and chronometers; he wrote *Micrographia*, the first systematic account of the microscopic world, including the discovery of cells; he introduced the telescope into astronomic measurement and invented the micrometer; and he shares with Papin the credit of preparing the way to the steam-engine.

Probably his greatest contribution to science is only now beginning to be recognized: his claim to have originated the idea of the inverse square law and universal gravity. Here, as we shall see, he was outclassed by the superb mathematical achievement of Newton, but it now seems that the basic physical ideas were Hooke's and that he was quite unjustly robbed of the credit for them (p. 336). Hooke's life illustrates both the opportunities and the difficulties that the gifted experimenter could find in the seventeenth century. It also brings out the enormous store of inventiveness and scientific insight that had lain concealed for thousands of years in the brains and hands of natural craftsmen.[8.21]

7.8—*MAKING THE NEW WORLD-PICTURE*

The accent of the period was one of *extensive* inquiry covering the whole field of Nature and the arts, and *constructive* theory in those parts where mathematical methods could be applied. It was no longer necessary, as it had been in the previous period, to concentrate on upsetting the physics of Aristotle or the physiology of Galen. The theories of Copernicus, Galileo,

and Harvey were almost unanimously accepted by the new *virtuosi*. Where they differed from their predecessors was in attempting to give them a deeper physical and philosophic meaning. First in the field was the system of Descartes with its emphasis on mere extension and the complete and continuous filling of the universe with subtle matter acting by impulsion from one part to another. It was the doctrine of the *plenum*.

The corpuscular philosophy: Gassendi

But there was another view, and a far older one, beginning to make itself felt. The attack on Aristotle left the way clear for Democritus and his atomic theory (p. 127). This was brought to the notice of the scientific world by a learned and penetrating mathematician and philosopher, Gassendi (1592–1655), a Provençal priest. If he had not been of a modest and retiring nature he would not have been so easily overshadowed by his contemporary, Descartes; for his influence on science was great. He was an astronomer of note—he was the first to observe the transit of Mercury—and one of the founders of meteorology, being the first to study parhelia (mock suns) and the aurora borealis. He did far more than resurrect the old atomic theories as set out by Epicurus and Lucretius; he turned them into a doctrine which included the Renaissance advance in physics. Gassendi's *atoms* were massive particles with inertia and they moved in the *vacuum* which Galileo's successors had proved to exist. His definition of atoms is that given, almost word for word, by Newton in his *Opticks* fifty years later. He put this view forward so persuasively that it was accepted, almost without their noticing it, by all those natural philosophers who had not sworn adherence to Descartes' plenum, with its vortices.

The *corpuscular hypothesis* was obviously well suited to the mathematical-mechanical bent of the time. Following the dynamics of Galileo and Descartes it was far easier to work out the motions of such small point-like particles than of a piece of homogeneous space. Thanks to Gassendi's piety the atoms were also purged of their atheistic and subversive associations (p. 128). He made explicit the implications of the new mechanics by demanding of God not the continuous operation of the material world, but only an impulse given to all the atoms at the beginning of time which should determine by divine providence all their future movements and combinations,

Philosophical instruments: optic glasses

The emphasis on experiment in the new science implies the use of apparatus and particularly of instruments made especially for the purpose. Nevertheless the material equipment of the new scientists was still of the simplest. Only telescopes had to be large and expensive. Almost any house could be filled with an *elaboratory* (or glorified workroom) which might hold a furnace with a few retorts and still heads, a balance, a microscope, and some dissecting instruments, one of the new air-pumps, a thermometer, and a barometer. Anything else was improvised. With such equipment the greatest discoveries in all branches of science could be made. It will be convenient to treat those in optics, pneumatics, chemistry, and physiology before passing on to the central theme of the mechanics of the heavens.

It was the practical and accidental discovery of the telescope at the beginning of the century that gave rise to a new interest in optics; for once an instrument exists the need to improve it leads to searching for explanations of how it works. In attempting to do so scientific principles leading to other instruments are discovered. Seventeenth-century optics grew largely out of the attempt to understand the nature of refraction, on which the telescope is based, and to remove the defects which it was soon observed to have.

On the first problem of the nature of refraction they had to start where Alhazen (p. 202) and his medieval followers, Dietrich of Freiburg and Witelo (p. 223), had left off 400 years before. They had established that rays were bent or broken—refracted—on meeting a denser medium. But they could not find the law of refraction and therefore could not calculate the action of a lens. The Dutchman, Snell (1591–1626), found the correct law, which Descartes appropriated and explained in terms of moving particles of light which needs must travel faster in the refracting body than the air, an unlikely conclusion which was to lead to much confusion later. With Snell's law, optics seemed to become part of geometry and it should have been possible to construct perfect telescopes. Actual telescopes, however, remained irritatingly imperfect. In particular, images of stars were seen surrounded by coloured haloes. That light passing through transparent bodies emerged with the colours of the rainbow had long been known. With the object of elucidating the rainbow the medieval scientists even carried

out extensive experiments on prisms, but had got no further than noting the fact that red light was least and blue was most refracted.[3.16] Descartes in his study of the rainbow was not able to improve on them. The solution of the problem of colour was only to be found by Newton, and was his first recognized achievement in physics. (His career will be treated later, pp. 337 f., in conjunction with his work on gravitation.)

Newton's "Opticks": the doctrine of colours

Newton had first tried to avoid the difficulty of coloured images by doing without the refraction which caused it. He built the first reflecting telescope (Fig. 11), the prototype of the giants of today and also of the more recent device, the reflecting microscope. Not satisfied with this he attacked the problem of colours directly, taking up the experiments of Descartes on the prism where he had left them. By a most brilliant combination of experimental technique and logic he was able to show that the colours of the prism, or of the rainbow, are not created by it but are the intrinsic components of ordinary white light. His researches, however, did not help him to solve his original problem; indeed he was able to show to his own dissatisfaction that it was impossible to correct the dispersive or colour-making properties of lenses. In this he was wrong, and his authority held up the practical development of telescopes for about eighty years. A Swedish mathematician, Klingenstjerna (1698-1765), seems to have been the first to repeat Newton's experiments with sufficient care to show his error. It was not until 1758 that Dollond, the instrument maker, hearing of Klingenstjerna's work, was able to use the idea of balancing two kinds of glass of different refractivities and dispersion against each other, so producing the achromatic lens which is the basis of all modern optical instruments.

Light as particles or waves: Huygens

Newton, in his optical studies, considered kinds of colour other than those of the rainbow, notably those produced by reflection from thin layers, such as oil on water. It was there he found the first hint of the discontinuity or "graininess" of both matter and light. This strengthened his conviction, already gained by philosophic inclination and mathematical

convenience, that matter is atomic. Unfortunately the same conviction caused him to follow Descartes and treat light as atomic, its rays being the trajectories of particles reflected just as a ball bounces off a wall. Other phenomena producing colours pointed to a different conclusion. Grimaldi (1618–63) had long before Newton studied the colours found at the edges of shadows, particularly those of fine slits or hairs. He also found that the rays of light were not quite straight but slightly bent—diffracted—on passing near an object. He put both phenomena down to waves, like the familiar ripples in water, or pulses of sound, with the different colours having different wave-lengths like the notes of music.

Huygens developed this idea mathematically and showed how the *wave theory of light* would account both for diffraction and the colours of thin plates. Moreover he explained, far better than Newton had, the curious property of Iceland spar (calcite) of showing objects seen through it as double. Here again, however, Newton's superior authority carried the day and the wave theory of light had to wait more than a century before it was rehabilitated (p. 412, 440).

The microscope: the new world of small things

Just as the telescope in the hand of Galileo had found the secret of the stars, that other optic glass, the microscope, in the hands of a number of seventeenth-century observers such as Malpighi, Hooke, Swammerdam (1637–80), and the incomparable Dutch clothier, Leeuwenhoek (1632–1723), opened up a new world of the very small.[4.39] Insects, the parts of plants, the small creatures that live in water, even the minute bacteria and the spermatozoa that carry the principle of generation, were all observed and became the objects of wonder, speculation, and argument. The anatomy of larger animals was also refined and Harvey's theory of the circulation of the blood fully confirmed. But whereas the telescope, whether nautical or astronomical, had from the very start a real, practical use, the microscope did not prove its value until 200 years later, in the hands of Koch and Pasteur, for combating bacterial disease. Largely for this reason these early microscopical studies did not immediately lead to any great development either of microscopy or biology; what was seen remained more amusing and instructive—in the philosophic sense—than of scientific or practical value.

The vacuum and the barometer

The development of *pneumatics* far beyond the bounds reached by the Greeks (p. 159) was the first great step forward in physics that was to lead rather to industrial than to astronomical and navigational consequences. The decisive discovery that brought it about, the actual production of the *vacuum*, was itself derived directly from practical hydraulics. Hitherto the existence of the vacuum had been a philosophic question to be settled by argument (p. 128); from 1643 it was to become a matter of practical demonstration. Galileo was, in his latter days, concerned with the reason why it was impossible to raise water by ordinary suction pumps more than about thirty-two feet. This fact, long known to miners and well-sinkers, had not hitherto attracted the attention of the learned. Galileo attributed it to the inability of a water column to bear its own weight, though he could find no satisfactory explanation why once it had broken it did not fall right down, and attributed this to a limited *horror vacui*.

It was not until the year after his death that his pupil Torricelli (1608–47) had the ingenious idea of using mercury instead of water, and was thus able to work with a column of manageable height, for in the inverted tube the mercury would not rise above thirty inches, thus giving the same pressure as the water column of fifteen pounds per square inch. He had the intellectual courage to see that the real explanation was that the pressure of the air held up the column of mercury, so that the instrument was a *barometer*, a means of measuring the weight of the atmosphere. The space at the top of the column was the real *vacuum* which Nature was supposed to abhor. Indeed, as we have seen (p. 144), Aristotle had already proved a vacuum to be impossible because air, opening in front and closing in behind, was needed for violent motion. Its discovery was a last and fatal blow to Aristotle's mechanics, though every effort was made to deny it or explain it away. Torricelli's explanation was, however, soon confirmed by Pascal's (1623–62) experiment of taking a barometer up a mountain and noticing the fall in pressure.

Von Guericke's air-pump

The story was then carried forward by a remarkable character, the prototype of the heavily endowed scientists of today, Otto von Guericke (1602–86), the mayor of Magdeburg and

ex-Quartermaster of Gustavus Adolphus, and a man of considerable means and great enterprise. Von Guericke did things in a big way; he spent £4,000, a stupendous sum in those days, on his experiments. He first of all tried to produce a vacuum by the straightforward method of pumping the water out of a closed barrel. The barrel burst, so he made a stronger vessel of brass. Afterwards he devised an air-pump and succeeded in producing vacua in large vessels. One of these he used for his celebrated experiment when sixteen horses a side were needed to pull apart two hemispherical vessels in the presence of the Emperor and his court. The Magdeburg hemispheres furnished a most impressive demonstration of the material truth of the new science. But the experiment did more than that; it showed people that the vacuum of the pressure of the air was a most powerful force that only needed ingenuity to harness it for useful purposes. Von Guericke himself thought of transferring power through evacuated tubes, an idea that was afterwards developed in the vacuum brake for the railways.

Von Guericke's pumps were much improved by Boyle, or more probably by Hooke, who was then in his pay. With this pump Boyle demonstrated many new and strange effects. He showed, for instance, that without air, sound could not travel, but light and magnetism were not affected. He also found what might have been expected, but was nevertheless a striking demonstration, that both life and combustion were impossible in a vacuum, and thus provided the first clues to the great chemical and physiological revolution of the next century.

The use of the air-pump, particularly the effort involved in pumping, led Boyle to a study of the behaviour of air, both compressed and expanded. Thus he discovered the first scientific law outside that of simple mechanics, what he called the " Spring of Air," the law that we now know as Boyle's Law: that the pressure multiplied by the volume of a certain amount of air is constant—or rather, as was found later, is directly proportional to the temperature.

The idea of using new natural forces to satisfy human needs had never entirely died out, and was bound to come up in an era of scientific enterprise such as the seventeenth century, when there was a mounting need of brute force to pump the mines and set going the wheels of flourishing industry. One obvious force to use was that of fire, especially ever since the power of

fire was made manifest in the cannon. One of the first crude ideas was an internal-combustion engine using gunpowder where we use petrol. After that inventors turned to the expansive power of steam. These direct methods were bound to fail, not because they were intrinsically wrong, but because the technique of the time did not provide vessels strong enough to deal with pressures of this magnitude. Denis Papin (1647–1712), Huygens' assistant, who afterwards worked for a while with Boyle, did manage to make a *digester* in which he reduced bones to soup, but his *pressure cooker* has only come into use in our own day. He also took the first steps to a practical steam-engine. The way to the use of steam power was to lead through the vacuum, as will be shown in the next chapter.

The false dawn of rational chemistry

The discovery of the vacuum furnished the first clue that might have led to the development of rational chemistry in the seventeenth century instead of 100 years later. The vacuum pump showed how air was necessary both to combustion and breathing, and centred interest on the twin problems of flame and life. Boyle, Hooke, and Mayow, following a clue dropped by Paracelsus, almost succeeded in proving that air contained something that was essential to burning and that turned arterial blood red. Boyle referred to it as " a little vital quintessence (if I may so call it) that serves to the refreshment and restauration of our vital spirits." Mayow called it " Nitro aerial spirit " thus linking it with gunpowder—which was to become Lavoisier's *oxygen*. But they got no further for two fundamental reasons: lack of suitable scientific theory and inadequate techniques and materials.

Chemistry had never been part of the classical canon, and the Aristotelian elements, earth, water, air, and fire, had always had a meteorological and physical aspect, rather than a chemical one (p. 122). Arab and medieval chemistry, or rather alchemy, was, however, thoroughly mixed with an astrology that linked the metals with the planets. The collapse of the Aristotelian–Platonic world-picture meant that chemistry without its airs and planetary influences had no intellectual basis left, as Boyle pointed out in *The Skeptical Chymist*. Nor did the Arabic–Paracelsan " spagyric " chemistry of the three principles—mercury, sulphur, and salt—fare any better (p. 272). The principles were far too vague and changeable to fit into a

corpuscular philosophy which was specifically designed to exclude *occult qualities.* Boyle himself managed to give a precise definition of an element, though a negative one:

> No body is a true principle or element . . . which is not perfectly homogeneous but is further resolvable into any number of distinct substances how small soever.

Unfortunately, the technique of chemistry could give no guarantee, apart from a few metals, as to what was an element; and Boyle's criterion was inapplicable for another hundred years. He recognized this himself in his essay *On the Unsuccessfulness of Experiments.*

Newton, who worked at chemistry for much longer than at physics, got no further in practice. In theory he had evolved, as Vavilov [4.85; 4.108] has shown, a picture of the atom composed of shell within shell of parts held together successively more firmly. This was a striking and quite logical anticipation of the modern atom with its electrons and nuclei, but it lay forgotten for nearly 300 years. In the seventeenth century chemistry was not yet in a state in which the corpuscular analysis could be applied. For that it needed the steady accumulation of new experimental facts that was to come in the next century. Chemistry, unlike physics, demands a multiplicity of experience and does not contain self-evident principles. Without principles it must remain an " occult " science depending on real but inexplicable mysteries.

As long as chemistry revolved around the same materials as were known to the Ancients, it tended to become stereotyped. But after the fifteenth century the chemical world expanded rapidly. New substances with remarkable properties, such as phosphorus, were accidentally produced, and new metals such as bismuth and platinum were discovered in the Old and New Worlds. To explain their properties new theories, continuously being checked by new practice, were needed. They were necessarily, at first, qualitative and obscure, but they formed an essential foundation to more precise theories. All the time, in response to the demands of an ever more specialized trade and industry, there came the need for particular chemicals —saltpetre, alum, copperas (iron sulphate), oil of vitriol (sulphuric acid), soda—which gave birth to a chemical industry from the experience and the problems of which was to come the rational chemistry of a later age.

Seventeenth-century biology

The world of living things, with its enormously greater complication, was bound to be far more difficult to explain than that of chemical transformation. It is therefore not surprising that the new mechanical, corpuscular philosophy, in spite of its pretensions, was of little real service. Sanctorius (1561–1636) weighed himself in a balance while eating and sleeping but could not explain the changes he observed. Descartes' idea of the animal-machine and the man-machine which differed only by the attachment of a rational soul steering it through the pineal gland did little to advance physiology. Borelli (1608–78) pushed the analogy further and accounted, on mechanical principles, for the limb movements of men and animals. Hydraulics had worked well for the heart and blood but were of little use for the brain and the nervous fluid.

Where the seventeenth century did make a critical advance was in observation, particularly in using the microscope (p. 328), which revealed for the first time the spermatozoa responsible for generation. More immediately important was the work of Nehemiah Grew (1641–1712), who laid the foundations of plant physiology, and of John Ray (1627–1705), a blacksmith's son, who took the first steps towards a scientific classification of plants and, less successfully, of animals.

The biological investigations of the late seventeenth century were, in practice, of little immediate use to agriculture. The changes that were made, and they were great, particularly in horticulture, were due rather to the careful and slow improvements of traditional practice under exceptionally favourable economic conditions. It was in Flanders and Holland that it was possible to find men of substance able and willing to put *capital* in the form of implements and manure into their farms and at the same time to be assured of an ample and growing market for the improved produce. Holland was the nursery from which the new methods, thanks to the work of enthusiastic amateurs like John Evelyn (1620–1706), were to pass to England (p. 283, *n*. p. 258).

The direct method of observation and experiment was to be more immediately fruitful in medicine, though progress was disappointingly slow. The idea that medicine was a science to be discovered from the study of patients rather than a doctrine to be practised on them, though as old as Hippocrates, had been largely forgotten. It was renewed in this time by doctors like

Sydenham (1624–89), who, besides being a great clinician, was in touch with all the science of his time.

7.9—*CELESTIAL MECHANICS: THE NEWTONIAN SYNTHESIS*

While all these achievements bear witness to the great flowering of scientific activity in many fields, the central interest and the greatest scientific triumph of the seventeenth century was undoubtedly the completion of a general system of *mechanics* capable of accounting for the motion of the stars in terms of the observable behaviour of matter on earth. Here the moderns were in effect settling their accounts once and for all with the ancient Greeks. Ancients and moderns were both agreed on the importance of the study of the heavens. But because the interests of the latter were now more practical than philosophic, they required a very different kind of answer. Finding that answer in a complete and satisfying form was the work of a sequence of mathematicians and astronomers, including almost all the great names of science of the period—Galileo, Kepler, Descartes, Borelli, Hooke, Huygens, Halley, Wren—but all was to lead up to the clear unification of mechanics in Newton's *De Philosophiæ Naturalis Principia Mathematica*, where he set out and proved his theory of universal gravitation.

The intrinsic interest of the problem of the movements of the solar system was still very great, though, in fact, its philosophical and theological significance had already vanished with the destruction of the cosmology of the Ancients. The trial of Galileo was indeed in the nature of a futile parting shot by clerical Aristotelianism. But the new edifice that was to take its place would not be complete unless an acceptable physical explanation of the system of Copernicus and Kepler could be found. That was one reason why almost every natural philosopher speculated, experimented, and calculated with the aim of finding this explanation. Some got very close to it, particularly Hooke, until Newton's success ended the chase.

Finding the longitude

The astronomers had another and even more compelling reason for discovering the laws of motion of the solar system. This was the need for astronomical tables far more accurate than

had sufficed in the days when astronomy was required mainly for astrological prediction. The needs of navigation were far more stringent. The determination of a ship's position at sea, and particularly the more difficult part of the position, the longitude, was a recurring problem. It became more and more urgent as a larger and larger share of the economic and military effort of countries was spent in overseas ventures, especially of those countries that were themselves the centres of scientific advance: England, France, and Holland. The finding of the longitude was a question that was to occupy both the learned astronomers and the practical sailors for many decades, even centuries. It was for the purpose of assisting in the solution of this practical problem that the first nationally financed scientific institutions were set up—the Observatoire Royal at Paris in 1672 and the Royal Observatory at Greenwich in 1675.

The question of the determination of longitude is essentially one of determining absolute time—or, as we now would call it, Greenwich time—at any place. This, compared with the local time, gives the time interval which is directly convertible to longitude. At any place there are, or were before the invention of radio, only two methods of determining the Greenwich time: one by observing the movements of the moon among the stars—a clock already fixed in the sky; and the other by carrying around an accurate clock originally set at that time. The first required extremely accurate tables for the prediction of the place of heavenly bodies, the second absolutely reliable clock mechanisms. All through the seventeenth and a large part of the eighteenth centuries both lines of attack were pursued without definite advantage falling to either. There was an immediate stimulus to thought, observation, and experiment in both directions, a stimulus in part simply mercenary but also one of national and individual prestige.

The chronometer

The two methods were at first sight quite different: one was concerned with a movement of some material-controlling mechanisms, the other with that of spheres in empty space; but as they were studied both were found to have a common basis in *dynamics*. It was Galileo himself who had discovered that the ideal controller, that beat constant time, was the *pendulum*. Hooke made the essential practical contribution of substituting

the spring-controlled balance wheel, which was not upset by the motion of the ship, for the pendulum. In either case accurate time-keeping depended on knowing the laws of motion of bodies in oscillation, and it was here that Huygens solved the problem and laid the basis of the first chronometer, as set out in his book *De Horologium Oscillatorium* (1673). But a long time had to pass before these principles could be turned into effective practice through improved workmanship, and Harrison's chronometer could in 1765 finally win the prize offered by the Admiralty for achieving the longitude.

Planetary motions : the doctrine of attraction

It was, however, the purely astronomical approach that, though it failed to provide the practical solution, was to prove far the more valuable to the science of the future. This was because of the stimulus it gave to the finding of a mathematical and dynamical solution to the problem of planetary motion. Many people had speculated as to why the planets should move round the sun in the orbits which Kepler had first shown were elliptical; they had even guessed that they might be held there by some force of attraction. In fact the idea of attraction had been a common one ever since Gilbert's study of the magnet (p. 299), and even before. The magnet showed that attraction was possible at a distance and Gilbert himself had suggested that what held the planets in their position and indeed drove them round their orbits might just be magnetism.

Borelli in 1666 introduced the important idea that the movements of planets implied the existence of the need to balance the centrifugal force, such as that exerted by a stone in a sling, by some other force which he characterized as the force of gravity extending beyond the immediate neighbourhood of the earth to the moon and from the sun to the planets. To account for an elliptical orbit, with the planet moving faster as it nears the sun, the force of gravity must increase to balance the increased centrifugal force. The force of gravity is therefore some function of the power of the distance. The question now became: What function? Hooke, who had already suspected that gravity diminished with the distance, tried to confirm it by looking, though in vain, for the variation of weight in a body on the ground, in a mine-shaft, and at the top of a steeple.

The prevailing theory of gravity remained that of Descartes: namely, that heavy bodies were sucked down to their centres of

attraction by "some secret principle of unsociableness of the ethers of their vortices," to quote Newton, who adhered to this theory as late as 1679.[4.79]

Things could go no further until these general ideas could be reduced to a mathematical form and checked with observations. The first step to this was taken by Huygens in 1673, when in connection with his work on pendulum clocks he enunciated the law of centrifugal force, showing that it varied as the radius and inversely as the square of the period. Now the square of the period, according to Kepler's third law, was proportional to the cube of the radius, and it follows therefore that the gravitational pull or centripetal force to balance the centrifugal force must depend on the radius divided by its cube, that is on the inverse square of the radius. Hooke, Halley, and Wren had made this deduction by 1679. Two problems remained: that of the explanation of elliptic orbits; and the mode of action of large attractive bodies. Hooke wrote to Newton, putting these problems, but received no reply, and in 1684 Halley offered a prize for their solution. It was clear that the answer was very near, but, though many men had led up to it, only one had the mathematical ability to find it and to draw the revolutionary conclusions that followed from it.

Isaac Newton

That man was Isaac Newton, one of the younger generation of Fellows—born in 1642, the year Galileo died—but already well known for his mathematical and optical researches. Newton came from the new rural middle class that had already produced Cromwell and the parliamentary officers. He was the posthumous son of a small Lincolnshire farmer with connections good enough to send him to Cambridge, where he studied with no particular distinction. In 1663 he came into contact with the learned and travelled Isaac Barrow (1630–77), the new Lucasian professor of mathematics, who appreciated his abilities and got Newton appointed to his chair in 1669 at the age of twenty-six, though he had published nothing and attracted little notice. He remained at Cambridge until at the height of his fame he was, in 1696, appointed Warden, and later Master of the Mint, at £400 a year, a job that he was considered very lucky to get and the duties of which he carried out conscientiously.

At Cambridge Newton worked on optics, many other

branches of physics, chemistry, biblical chronology, and theology of a heretical, Arian kind. He seems to have had but little influence on the University and never founded a school. It was there that he came under the influence of a deeply religious group of Platonists led by Henry More, and through them Platonic elements entered into his philosophy and consequently into that of modern science.[4.28] In general he conformed to the views of his class, represented Cambridge University in Parliament, and supported the Whig compromise in politics. This helped to make his ideas, which were only later to show their revolutionary potentialities, appear respectable at the start. Newton was personally an extremely odd character, very reserved and retiring, even secretive. He never married and would not accept ordination because of his doubts about the Trinity. He knew enough to make him very self-critical; but this made him even more resentful of the criticisms of other people.

Newton's public entry into the discussions of gravitation came late. He may very well have considered it when, as an undergraduate, he had to retire to his home at Woolsthorpe in the plague year, 1665, and the story of the apple may be a true one. Either, however, he had doubts about it or he did not consider it very important, for he published nothing on it and busied himself with other things for twenty years. His later work shows him capable of entertaining a number of incompatible hypotheses before deciding on one, and he may have done so here, as his Cartesian speculation of 1679 shows (p. 337). In any case what he thought in 1665 can have had no influence on the course of science, and the inverse square law was certainly arrived at by several others before he published it.

Newton's contribution was, nevertheless, the decisive one. It lay in finding the mathematical method for converting physical principles into quantitatively calculable results confirmable by observation, and conversely to arrive at the physical principles from such observations. In his own words from the preface of *Principia*:

> I offer this work as the mathematical principles of philosophy, for the whole burden of philosophy seems to consist in this—from the phenomena of motions to investigate the forces of Nature, and then from these forces to demonstrate the other phenomena; . . . I wish we could derive the

rest of the phenomena of Nature by the same kind of reasoning from mechanical principles, for I am induced by many reasons to suspect that they may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards one another, and cohere in regular figures, or are repelled and recede from one another. These forces being unknown, philosophers have hitherto attempted the search of Nature in vain; but I hope the principles here laid down will afford some light either to this or some truer method of philosophy.

The infinitesimal calculus

The instrument by which he did this was the infinitesimal calculus or, as he called it, the method of fluxions (the even flowing of a continuous function). This marked the culmination of the work of many generations of mathematicians, from Babylonian predecessors through Eudoxus and Archimedes (p. 130). In the seventeenth century it was rapidly developed through the work of Fermat and Descartes. It was put in the form we know it by Leibniz (1646–1716) (p. 364). Whether Newton or Leibniz deserves the greater credit for it—a subject of bitter controversy at the time—is not, from the point of view of the progress of science, of any great moment. What is important is that Newton used his calculus to solve vital questions in physics and taught others to do the same.

By its use it is possible to find the position of a body at any time by a knowledge of the relations between that position and its velocity or rate of change of velocity at any other time. In other words, once the law of force is known, the path can be calculated. Applied inversely, Newton's law of gravitational force follows directly from Kepler's law of motion. Mathematically they are two different ways of saying the same thing; but whereas the laws of planetary motion seem abstract, the idea of a planet held in its course by a powerful attraction is a graspable image, even if the gravitational force itself remains a complete mystery.

The calculus, as developed by Newton, could be used and was used by him for the solving of a great variety of mechanical and hydrodynamic problems. It immediately became the mathematical instrument for all understanding of variables and motion, and hence of all mechanical engineering, and remained almost the exclusive one until well into the present

century. In a very real sense it was as much an instrument of the new science as the telescope.

The "Principia"

It must have required all Halley's persuasiveness to make Newton, in the two years 1685–86, embody his solution of planetary motions in his *Philosophiæ Naturalis Principia Mathematica.* It was printed for the Royal Society and bears the imprint of its President, who was rather surprisingly Samuel Pepys, but the Society was short of money and Halley had to pay for its production out of his own pocket. This book, in sustained development of physical argument, is unequalled in the whole history of science. Mathematically it can only be compared to Euclid's *Elements*; in its physical insight and its effect on ideas only to Darwin's *Origin of Species*. It immediately became the bible of the new science, not so much as a revered source of doctrine—though there was some danger of this, especially in England—but of further extensions of the methods there exemplified.

Newton, in his *Principia,* did far more than establish the laws of motion of the planets. His grand object was certainly to demonstrate how universal gravity could maintain the system of the world. But he wished to do this not in the old philosophical way but in the new, quantitative, physical way. In this he had two other tasks to fulfil: first of all to demolish previous philosophic conceptions, old and new; and secondly to establish his own as not only the correct but also the most accurate way of accounting for the phenomena.

A great deal of the *Principia* is taken up with a careful and quantitative refutation of the system most in vogue and with which he himself had flirted, that of Descartes with its set of whirlpools in which each planet was held. This was a genial intuitive idea but one totally incapable, as Newton showed, of giving accurate quantitative results. In doing so, he was led into founding the science of *hydrodynamics,* discussing and refining the ideas of *viscosity* and the resistance of the air, and indeed laying the basis for a mechanics of fluids that was to come into its own only in the day of the aeroplane.

Though Newton used the calculus in arriving at his results, he was careful in the *Principia* to recast all the work in the form of classical Greek geometry understandable by other mathematicians and astronomers. The immediate practical conse-

quence of its publication was to provide a system of calculation enabling the positions of the moon and planets to be determined far more accurately, on the basis of a minimum of observations, than his predecessors could by their empirical extension of long series. Three observations, for instance, were sufficient to fix the position of a celestial object for an indefinite future.

The proof of this was furnished soon after Newton's time by his friend Halley in his famous comet, whose return he successfully predicted on the basis of Newton's theories. As a result of using Newtonian theories nautical tables became far more accurate. Unfortunately, the most suitable celestial object to observe for the purpose of finding the longitude is the moon, and the moon's motion is quite the most complicated in the solar system. It was never reduced to good enough order to be a reliable guide to sailors, and in the end it was the scientifically minded clockmakers who took the prize—or as much of it as they could persuade the Admiralty to part with—from the mechanically minded astronomers.

Newton replaces Aristotle: an established universe against a maintained one

Newton's theory of gravitation and his contribution to astronomy mark the final stage of the transformation of the Aristotelian world-picture begun by Copernicus. For a vision of spheres, operated by a first mover or by angels on God's order, Newton had effectively substituted that of a mechanism operating according to a simple natural law, requiring no continuous application of force, and only needing divine intervention to create it and set it in motion.

Newton himself was not quite sure about this, and left a loophole for divine intervention to maintain the stability of the system. But this loophole was closed by Laplace (p. 363) and God's intervention dispensed with. Newton's solution, which contains all the quantities necessary for the practical prediction of the positions of the moon and the planets, stops short of any fundamental questioning of the existence of a divine plan. Indeed Newton felt he had revealed this plan and wished to ask no further questions.

He got over the awkward assumption he had made on the existence of absolute motion by saying, following his Platonist friends, that space was the sensorium—awareness or brain—of God, and must therefore be absolute. In this way he avoided

confusing himself in relativistic theories. His own theory gave no reasons why the planets should all be more or less in a plane and all go round the same way—for which Descartes' whirlpool had given a facile explanation. Newton honestly disguised his ignorance of origins by postulating that this was the will of God at the beginning of creation.

By this time the destructive phase of the Renaissance and Reformation was over; a new compromise between religion and science was needed just as much as those between monarchy and republic and between the upper bourgeoisie and the nobility. Newton's system of the universe did represent a considerable concession on the part of religious orthodoxy, for by it the hand of God could no longer be clearly seen in every celestial or terrestrial event but only in the general creation and organization of the whole. God had, in fact, like his anointed ones on earth, become a constitutional monarch. On their side the scientists undertook not to trespass into the proper field of religion—the world of man's life with its aspirations and responsibilities. This compromise, wisely advocated by Bishop Sprat, and preached by the redoubtable Dr Bentley in his Boyle sermons of 1692, was to last until Darwin upset it in the nineteenth century.*

Although the system of universal gravitation appeared to be at the time, and still remains, Newton's greatest work, his influence on science and outside it was even more effective through the methods he employed in achieving his results. His calculus provided a universal way of passing from the changes of quantities to the quantities themselves, and vice versa. He provided the mathematical key adequate for the solution of physical problems for another 200 years. By setting out his laws of motion, which linked force not with motion itself but with change of motion, he broke definitely with the old common-sense view that force was needed to maintain motion, and relegated the friction, which makes this necessary in all practical mechanisms, to a secondary role which it was the object of the good engineer to abolish. In one word Newton established, once and for all, the *dynamic* view of the universe instead of the *static* one that had satisfied the Ancients. This transformation, combined with his atomism, showed that Newton was in unconscious harmony with the economic and social world of his time, in which individual enterprise, where each man paid his way, was replacing the fixed hierarchical order of the

late classical and feudal period where each man knew his place.*

Quite apart from these actual achievements, Newton's work, itself that final refinement of a century of experiment and calculation, provided a reliable method which could be used confidently by the scientists of later times. At the same time it reassured scientists and non-scientists alike that the universe was regulated by simple mathematical laws. Thus the laws of electricity and magnetism, as we shall see (p. 434), were built on a Newtonian model, and the atomic theory of the chemists was a direct outcome of Newton's atomic speculations.

The prestige and influence of Newton

The very successes of Newton carried with them corresponding disadvantages. His abilities were so great, his system so apparently perfect, that they positively discouraged scientific advance for the next century, or allowed it only in regions he had not touched. In British mathematics this restriction was to remain until the mid-nineteenth century. Newton's influence lasted even longer than his system, and the whole tone he gave to science came to be taken so much for granted that the severe limitations it implied, which were largely derived from his theological preconceptions, were not recognized till the time of Einstein and are not fully even now.

Paradoxically, for all his desire to limit philosophy to its mathematical expression, the most immediate effect of Newton's ideas was in the economic and political field. As they passed through the medium of the philosophy of his friend Locke and his successor Hume, they were to create the general scepticism of authority and belief in *laisser-faire* that were to lower the prestige of religion and respect for a divinely constituted order of society. Directly through Voltaire, who first introduced his work to the French, they were to contribute to the "Enlightenment" and thus to the ideas of the French Revolution. To this day they remain the philosophical basis of bourgeois liberalism.

7.10—*RETROSPECT: CAPITALISM AND THE BIRTH OF MODERN SCIENCE*

Looking back over the epic movement of the new science in the fifteenth, sixteenth, and seventeenth centuries we are now

better placed to see why the birth of science occurred when and where it did. We can see how it followed closely on the great revival of trade and industry that marked the rise of the bourgeoisie in the fifteenth and sixteenth centuries and its political triumph in England and Holland in the seventeehth. The birth of science follows closely after that of capitalism. The same spirit that broke the fixed forms of feudalism and the Church had also broken with the even older slave-owning, conservative tradition of the classical world. In science, as in politics, a break with tradition meant a liberation of human ingenuity into hitherto closed fields. No part of the universe was too distant, no trade too humble, for the interest of the new scientists.

The unity of seventeenth-century science

Yet despite the variety of fields of study, science in the seventeenth century had an underlying unity which had a threefold basis: that of persons, of ideas, and of applications. In the first place, the scientist of the seventeenth century was himself able to cover and to produce original work over all the field of then known science. Newton was not only a mathematician, astronomer, optician, and mechanic, but he worked for years on chemistry, of which, though he published little, it appears he had a far deeper understanding than any other man of his time. Hooke, though no great mathematician, worked, as we have seen, in all these fields as well as in physiology, and is one of the pioneers of microscopy. Wren, whom we know as an architect, was also at the very centre of the scientific movement. As a result of this universality the scientists or *virtuosi* of the seventeenth century could get a more unitary picture of the field of science than it has been possible to achieve in later times.

Mathematical philosophy

In the second place, there was an underlying unity produced by a guiding idea and method of work that was essentially mathematical and based on a mathematics derived directly from the Greeks, but including also Arabic, Hindu, and possibly Chinese contributions. This was not sheer gain; an effective, though unrecognized, limitation of the field of seventeenth-century science was due to this preoccupation with mathematics. Those parts of experience that could not then be

reduced to mathematics tended to be left out, and even those parts which were not suitable for mathematics tended to be treated mathematically, with somewhat ridiculous results. A follower of Harvey, for example, tried to explain the action of the different glands of the body by the relative momentum of their particles, which depended on the angles at which their ducts discharged. The extreme case was in the social field, with the attempt by Spinoza (1632–77), the noblest of the seventeenth-century philosophers, to reduce ethics to mathematical principles. It was because of the insistence on mathematics that the scientists of the seventeenth century succeeded only in those fields, such as mechanics and astronomy, where the Greeks had been before them, and made little significant progress in chemistry and biology.

Science and technical problems

The third and most characteristic unifying principle of the new science was its concern with the major technical problems of the day. As we have seen, the enormous advance of technique from the fourteenth century, or even before, arose out of the break with tradition in the favourable circumstances of Europe, where abundant resources had to be exploited by few men, thus putting a premium on ingenuity. The solutions reached in mining and metal-working, transport and textiles, were technical solutions, but by breaking with tradition they raised new problems which modern science was created to solve. Enough of these problems, especially those of navigation, gunnery, and mechanics, lay within the scope of the Greek tradition of learning to be within range of immediate practical solution. The remainder were to form the inspiration of eighteenth-century science.

Science proves its worth

It is true that at first the scientists claimed to be able to achieve greater results than were possible at the time. Until the end of the eighteenth century science drew far more from industry than it could yet give back. In chemistry and biology it was to be at least another hundred years before anything that the scientists could propose could replace or improve on the traditional processes, in medicine even longer. Even among the well-understood physical sciences, both in mechanics and gunnery, the practical man still held the advantage. The

improvement of mills was for long to be in the hands of the millwrights, that of guns in those of the founders. Working in wood or in roughly cast metal it was impossible to make use of the refinements which the new mathematics and dynamics could provide. Newton, for instance, did work out the trajectory of shot allowing for the resistance of the air. His methods were still being used in the Second World War, but they were quite inapplicable in his time. Gun barrels were uneven, the shot did not fit them, the quality and quantity of powder varied with every filling, and there was no means other than rough manhandling with ropes and wedges for pointing the gun. The practical gunner, who knew the limitations of his art, could well dispense with ballistics.[4.50] The only exception to this was the art of the clockmaker, in the higher reaches of which—the design of marine chronometers—some knowledge of dynamics was a necessity.

The one great success of the new science lay in navigation. This was achievement enough, for it was at a time when control of the sea-ways and the opening up of the new world were the key to national, economic, and political success. By proving its worth there, science became an established part of the new dominant capitalist civilization. It acquired a continuity and a status that it was never to lose. The importance of science was to grow relatively and absolutely as it came to be realized that the military and economic superiority of European civilization over the old civilizations of Islam, India, and China, was due to its technical achievements, and that the improvement of technique required the continuous application and development of science.

Ancients and moderns

It was in this field of techniques that the men of the seventeenth century felt superior not only to their forebears of the Renaissance and of the barbarous Middle Ages, but even to the almost legendary achievements of the ancient Greeks and Romans. Modern men, it was felt, might not be wiser or better, but they were certainly more ingenious and could do things the Ancients never dreamed of, like shooting off guns or sailing to America. More important than the achievement itself was the knowledge that it was only a beginning, that there was no limit to possible advance along the same line. As early as 1619 Johan Valentin Andrae, Comenius' tutor, had de-

clared, " It is inglorious to despair of Progress," and that idea, so foreign to the medieval, if not entirely to the classical mind, was launched on its triumphant career.[4.46]

Indeed it was towards the end of this period that the battle between Ancients and Moderns was most consciously engaged. It ranged with varying fortunes all over the world of knowledge.[4.61] Its most famous expression was Swift's *Battle of the Books* where the Moderns certainly get the worst of it. But Swift here, as in *Gulliver's Travels*, was swimming against the stream. However much they might still ornament the libraries of gentlemen the classics were for all practical purposes dead. They might still be authorities for the composition of sonorous prose but they had nothing to contribute to philosophy as the eighteenth century understood it.

Progress was still rather an ideal than an achievement. The great transition of the fifteenth, sixteenth, and seventeenth centuries had not brought about any revolutionary change in the material mode of life. That was still to come. Wealth and poverty had been redistributed. There were far more well-off people in England and the Low Countries at the end of the period than at the beginning, though probably fewer in Italy. What was important was that the method of multiplying wealth by turning it into capital had now broken through the feudal restrictions and the way was open to its indefinite extension. Under capitalism in its first phase the new incentive of profit was putting a premium on technical advance. The financial structure was, however, top heavy and unstable from the start. The merchants and gentlemen of the seventeenth century, for all their wealth and occasional interest in science, were not the men to make use of the new possibilities; but they

TABLE 4.—*The Scientific Revolution*

(*Chapter 7*)

This table attempts to present some of the major features of the birth of modern science in their relation to political, economic, and technical developments. The time-scale of the period, 1400–1700, is uniform, but the phases corresponding to the sections of Chapter 7 are indicated. This brings out the great concentration of effort in the last of these phases. The major critical discoveries and theories, such as Copernicus's vindication of the solar system, Harvey's circulation of the blood, and Newton's theory of gravitation, are specially indicated. The table has been drawn up to bring out the most significant relationships. Owing to their complexity, however, other relations, such as those between Harvey's discovery and the study of pumps, are not shown here, though some of these are given in Table 8.

TABLE

	HISTORICAL EVENTS	PHILOSOPHY	NAVIGATION	MATHEMATICS AND ASTRONOMY
	Authorities Reinstated →	*PLATO*	*GERSON*	*ARCHIMEDES, ARISTARCHUS*
	Dethroned →	*ARISTOTLE*		*PTOLEMY*
—1440	**Italian Renaissance** **Platonic academies in Florence** **Great growth of trade and arts**	**Humanism return to the classics**	**Portolan maps** **School of Sagres** **Portuguese along African coast**	**Recovery of Greek mathematics** ***Peurbach* revival of astronomy** ***Müller* nautical almanacs**
(Chap. 7.1–7.3)	**Italian wars**		**Columbus discovers America** ***Vasco da Gama* reaches India**	
1500	***Francis I* College de France** **Reformation** ***Luther*** ***Calvin***	**More "Utopia"** ***Vives, Erasmus, Rabelais,* criticism of medievalism**	**Magellan round the world**	
—1540				
1550	**Great inflation** **Counter Reformation** **Religious wars in France**		***Nunez* maps and navigation**	**Copernicus SOLAR SYSTEM** ***Tartaglia, Cardan,* algebra revived**
(Chap. 7.4–7.6)	**Revolt of Netherlands**	***Montaigne* scepticism**	**Problem of longitude** ***Mercator's* maps**	
	Elizabethan age **Gresham College**	***Bruno* plurality of worlds**	***Norman* magnetic dip**	***Vieta* symbolic algebra** ***Tycho* accurate observations**
1600	**Capitalism coming to power** **Accademia de Lincei** **Thirty Years War** **Civil wars in Britain** **Informal meetings of scientists**	**Bacon experimental philosophy** **Gassendi atomism** **Descartes mechanical philosophy** ***Hobbes* materialism**	**Gilbert on magnet**	**Kepler planetary orbits** ***Napier* logarithms** ***Descartes* analytical geometry** ***Fermat* number theory**
—1650	**Royal Society** **Louis XIV in France**	***Spinoza* rational morality**	***Guericke* frictional electricity**	**Newton calculus, THEORY OF GRAVITATION**
(Chap. 7.7–7.9)	**Académie des Sciences**			***Leibniz* differentials**
	Expulsion of the Huguenots			
—1690		***Leibniz* pre-established harmony**	↓ **Electricity**	↓ **Mathematical Physics**

Optics	Mechanics and Hydraulics	Chemistry	Medicine, Physiology, and Natural History
ALHAZEN	*PHILOPONOS*	*LULL*	*ARISTOTLE*
	ARISTOTLE		*GALEN*
Developments in painting and perspective	**Developments in metallurgy, mining and pumping**	**Beginnings of chemical manufacture, alcohol, gunpowder, alum**	
		Alchemy turns to chemistry	
Leonardo da Vinci **Scientific painting**	**Engineering, waterworks**	**Leonardo da Vinci**	**Drawings of anatomy and natural history**
Dürer **perspective**	**Development of gunnery**	**Paracelsus revival of chemistry** ***Agricola*** **" De Re Metalica "**	***Paré*** **surgery** **Vesalius " De Fabrica"**
			Servetus **pulmonary circulation** **Collection of rarities** **Development of gardening and agriculture**
	Tartaglia **ballistics**		
Spectacle-makers invent telescope	**Development of dykes, canals, and locks, in Holland** ***Stevin*** **statics and hydraulics**		
Galileo Telescopic observation, " Two chief systems " Trial	**Pendulum, " Two new sciences", Dynamics**	***Van Helmont*** **gas**	
	Scientific study of pumps		**Harvey circulation of blood generation of animals**
Newton **theory of colour** ***Römer*** **velocity of light** ***Huygens*** **wave theory of light**	**Torricelli barometer** **Guericke vacuum** **Boyle gas law** ***Hooke*** **experimental physics**	***Boyle*** **" Skeptical Chymist "** **Combustion**	***Leeuwenhoek*** **microbiology** ***Malpighi*** **microscopical anatomy** ***Mayow*** **theory of respiration** ***John Ray*** ***Nehemiah Grew*** **Classification of animals and plants**
↓	↓	↓	↓
Optical instruments	**Steam Engine**	**Rational Chemistry**	**Scientific Biology**

had cleared the ground for the flourishing of a humbler set of manufacturers, who were, thanks to science, to make use of and develop the traditional techniques of civilization out of all recognition.

The intellectual revolution

It would, however, be entirely wrong to consider the driving force of science as completely utilitarian. Science still carried much of the prestige, political and ethical, of the philosophy of the ancient world to which the Renaissance had added so greatly. Natural philosophy, as it was called, was a worthy, even noble profession and its patrons, in supporting it, were adding lustre to the State. The men of the new experimental science felt that it was they, rather than the schoolmen, who were the true heirs of the Ancients; and in fact the only parts of the external world where their methods succeeded were those already cultivated by the Greeks. Nevertheless, while the mathematics of Greece was one characteristic tool of modern scientific method, the whole intellectual movement of science arose out of the struggle against the philosophy of Greece, adapted as it had been in the Middle Ages to the service of a now outmoded feudal system. In its early phases the new experimental science was necessarily critical and destructive; in its later phases it aimed at providing a new basis for a philosophy more in tune with the needs of the times. The break was never complete; the hold of religion, both internal and imposed by society, was still too great to allow much deviation from the general scheme of creation and salvation accepted by Catholics and Protestants alike. Explicitly with Bacon and Descartes and even in the more cautious implicit philosophy of Galileo and Newton great liberties were nevertheless taken with the scheme of the divine governance of the world. These were in the next century to be the basis of criticism of the whole framework of religion.

The paradox of the Scientific Revolution was that those who contributed most to it, substantially the scientific innovators from Copernicus to Newton, were the most conservative in their religious and philosophic outlook. If they were not orthodox it was only because they thought that orthodoxy had wandered from the path of reason. They accepted the programme of St Thomas Aquinas of reconciling faith and reason, but they were forced to reject his conclusions because the scheme of the world

to which he had reconciled his faith was now revealed to be palpably absurd. Their own forms of reconciliation were to prove even less durable. But the day of theological domination over science had ended. It could still distort and delay the advance of science, but it could not stop it. Religion was tacitly confined to the moral and spiritual sphere. In that of the material world the Scientific Revolution, willed or unwilled, had definitely taken place.

Science established

By 1690 science had definitely arrived. It had acquired an enormous prestige, at least among the upper ranks of the society of the time. It had its organization in the Royal Society and the Académie Royale des Sciences, which were closely linked by personal ties with the ruling powers—with Parliament and the great Whig houses in England, with the Royal Court in France. It was spreading to other countries. A coherent discipline of experiment and calculation had been evolved, a coherent method by which any kind of problem could sooner or later be tackled. The foundations of science might later be underpinned and altered, but the edifice raised on them was stable, and, even more important, the general method for raising it was now known and was never likely to be forgotten again.

However, the very success of the early scientific method had elements of danger in it. The method itself incorporated much of older ideas which inevitably coloured the thoughts of the first scientists, and enshrined them, as well as the new conceptions derived from experiment, in the new philosophy of science. It is this unconscious relic of the past that is now appearing in much of the idealistic scientific theories of today; and it may well be that the task of twentieth-century science will be to break up the system of Newton just as the seventeenth century broke up that of Aristotle.

PART V
SCIENCE AND INDUSTRY

INTRODUCTION

Capitalism and science

THE eighteenth and nineteenth centuries were the great formative centuries of the modern world, centuries that appeared to those who lived in them as representing a liberating phase of human development in which man had at last found the true way to prosperity and unlimited progress. To us, with the experience of the disturbances and changes of the twentieth century, they appear as centuries of preparation, centuries in which great things were done at the expense of much human suffering to produce a grandiose but unstable culture. They cover the period of the establishment of science as an indispensable feature of a new industrial civilization. The new methods of experimental science elaborated in the seventeenth-century revolution were to be extended over the whole range of human experience and at the same time their applications were to keep pace with and infuse the great transformation of the means of production which we call the *Industrial Revolution.*

The Industrial Revolution was not mainly, and certainly not in its first phases, a product of scientific advance, though certain contributions of science, notably the steam-engine, were to be essential ingredients in its success. Nevertheless the whole movement was far more closely identified with the growth and inner transformation of the economic system of *capitalism*, from the phase dominated by merchants and small manufacturers to one dominated by financiers and heavy industry.

It is no accident that the intellectual formulations of science, the technical changes of industry, and the economic and

political domination of capitalism should grow and flourish together at the same times and in the same places. The relations between them are, however, by no means easy to unravel. Techniques, economic forms, and scientific knowledge were all growing and changing rapidly in the period; sometimes one seems to take the lead, sometimes another. It will be our task in this section in particular to try to disentangle the contributions of science to technical and economic transformations as well as to trace the effect of these transformations on the growth and character of science itself. This, however, can become apparent only after a more detailed study of particular aspects of interrelation, and conclusions can be discussed only at the end of the section.

At the outset, however, it is necessary to give a broad description of the social and economic changes of the period so that those of science can be seen in adequate perspective. Already by the end of the seventeenth century the stage was set for the further advance of the new—capitalist—mode of production. In what was still but a small corner of Europe, almost limited to England, the Low Countries, and northern France, the urban middle class had broken away to a greater or lesser degree from feudal limitations; they could finance production for profit with an ever-increasing market for their products all over the world which the new navigation had opened to them. Production was still handicraft and domestic, but merchants and capitalist *manufacturers* were coming to control it more and more, and both craftsmen and peasants were being depressed to the status of wage labourers.

With the combination of an expanding market, growing freedom from manufacturing restrictions, due to a break-up of urban guilds, and a field of investment in profitable enterprise, there was a premium on technical innovations such as textile machinery, and also on revolutionary scientific inventions such as the steam-engine, which could cut costs and expand production and profits. Better organization of labour, the division and specialization of tasks, the factory system, and ultimately power-driven machinery, were all means to this end, and all drew from it the social drive necessary to break down the older-established systems of production. Once this process started in the latter part of the eighteenth century it tended to grow and spread to other fields by its own success based firmly on the new capital it generated. By the mid-

nineteenth century the domination of capitalism over the whole world was unquestioned, but that very fact did more than put a limit to its expansion. It made evident a fundamental instability from which it could not escape. By its very nature production for profit could never allow a sufficient share of goods or opportunities for the vast new population of wage labourers that it had brought into existence to provide for a continuous prosperity (p. 795). Booms were followed by slumps of increasing severity and the competition for limited markets provoked international rivalries. The open breakdown of the system was, however, not to begin till the twentieth century. For most of the period we are discussing here, the progress of science occurred against a background of an expanding industrial capitalism which tended to make more and more calls on it.

Technique and science

Though in their first stages changes of technique in response to economic needs could and did take place without any intervention of science, it often happened that the mere following of existing trends led to unforeseen difficulties which could be removed only by invoking science. For example, a natural source of supply such as a vegetable dye might run short, due merely to an increased production of cloth, thus creating a demand for an artificial substitute that could be found only through the help of science (p. 458). Or to take another example, the transition from home to large-scale brewing might in itself provoke disastrous failures which could be prevented by an appeal to science (p. 471).

This ancillary, almost medical, role of science in industry was, towards the end of the nineteenth century, replaced by a more positive one. Ideas originating in the body of science itself were developed to form new industries. The first and most important of these was the steam-engine—the *philosophical engine* of the early eighteenth century; but once its general principles became familiar its manufacture and use were absorbed into practical engineering. It is only at the end of the nineteenth century that industries that started and remained scientific, such as the chemical and electrical industries, began to take form, and their full development was not seen till the twentieth century.

Despite the contribution of the steam-engine it cannot be

claimed that science was a major factor in effecting the decisive change from hand to machine production that took place in the last quarter of the eighteenth century. This new method of production proved to be, on the other hand, a great forcing house for scientific knowledge. In the nineteenth century the situation began to alter. Science came to be a major agent for effecting technical developments. Its full integration into the productive mechanism had to wait till the twentieth century.

The relation of science to the history of the period is, however, by no means confined to its role in the productive process. The new form of society based on money exchange was taking form, with its emphasis on liberty and individual enterprise in contrast to the fixed status and social responsibility of the Middle Ages. This society, limited by class and by country as its benefits were, required a new set of ideas to express and justify itself. It found them, to a large extent, in the methods and results of the new sciences, while they in their turn were profoundly, though unconsciously, influenced in the formulation of their theories by prevailing social beliefs.

The scientific and industrial revolutions

It may appear somewhat arbitrary to divide, at the beginning of the eighteenth century, an Industrial Revolution from the Scientific Revolution of the seventeenth. There is naturally no question of the unbroken continuity between them. It might seem better to treat them as successive phases in one great transformation. Nevertheless, it seems to me that the distinction is more than one of convenience. There is a noticeable difference in quality between the two periods. The breakthrough in the former was essentially in understanding, in the second in practice. It is tempting to think of this as a relation of cause and effect, but the real relations are, as I hope to show, far more complex. To a certain extent the two evolutions of knowledge and power ran in parallel, driven by separate internal influences, though always reacting on each other, especially in periods of rapid advance (pp. 867 f.). Towards the end of the seventeenth century a third, economic factor, the expression of capitalism in manufacture, makes itself felt. It is to this that we may look for the transition of the mathematical-astronomical-medical science of the seventeenth century to the chemical, thermal, and electrical science of the eighteenth.

The nature of the complex interaction of science, industry, and society will, I hope, be more evident from actual examples of the history of this interaction contained in the following two chapters.

Phases and aspects of the growth of industry and science

In order to follow these interactions concretely over a period so rich and complex, without losing sight of the unity and continuity of the historic process, the best method I have been able to find is to operate here a double system of division by period and by subject, providing a kind of cross classification. These two divisions will be found successively in Chapters 8 and 9, followed by a general conclusion.

The division by sub-periods is, in Chapter 8, a particularly difficult one, partly because the wealth of information available prompts minute subdivision, but even more because of the impossibility of finding divisions applicable at the same time to political, economic, technical, and scientific history. Politically, for instance, the great divide is most evidently that of the French Revolution and the Napoleonic wars; these, however, provoked no loss of continuity but rather a general enhancement of scientific activity. The decade 1760–70 is, on the other hand, a turning point in technical and scientific history (p. 391), but is not so noticeable in the political sphere. Sometimes the divisions nearly coincide, as in 1831, when reform in politics and science come together—by no means accidentally, as they were advocated by the same men and supported by the same popular movements (p. 391).

My final choice has been to divide the whole period into four major phases. First comes the transitional or latent phase (8.1) leading up to the Industrial Revolution, that is from 1690 to 1760. The second phase (8.2–8.4) includes the whole movement of the French Revolution, from 1760 to 1830. This phase is as revolutionary in technique and in science as in politics, covering as it does the major advances of the Industrial Revolution and the Pneumatic or Chemical Revolution, second only in importance to the Mathematical–Mechanical Revolution of the seventeenth century.

The third phase (8.5–8.6) is the mid-nineteenth century, from 1830 to 1870, what has been called the heyday of capitalism. Finally the fourth phase (8.7–8.8) is a very short one, from 1870 to 1895, which in the outer world marked the be-

ginning of modern imperialism and in science the transitional period before the great twentieth-century revolution.

The second and third of these phases include two notable periods of advance and triumph of science. The first was, after the heroic age of the seventeenth century, rather a scientific backwater, a taking breath and preparing for the advance that was to come. And, in a different way, so was the fourth phase, though in both cases those working at the time felt they were completing a grand edifice: in one case the edifice of Newtonian physics, in the other the great physical synthesis of Faraday and Maxwell, and the great biological syntheses of Darwin and Pasteur.

Even with such a division of the period the general surveys of science in its historic setting, such as have been given in earlier chapters, will no longer suffice to provide an adequate picture of its now increasingly separate disciplines. For this purpose an attempt is made in the succeeding chapter (9) to follow out the development of five of the major lines of technical and scientific advance over the whole period of the eighteenth and nineteenth centuries. Those selected are: 9.1, Heat and Energy, including the history of the steam-engine; 9.2, Engineering and Metallurgy, with particular reference to iron and steel; 9.3, Electricity and Magnetism; 9.4, Chemistry; and 9.5, Biology.

In each section the aim is to bring out the inner coherence and continuous tradition of the field of activity, to illustrate the interplay of economic, technical, and scientific factors, and to bring out the interrelations of different sciences and techniques. Only after both time and subject divisions have been completed will an attempt be made to combine the two approaches and to try to draw from them general conclusions about the position and influence of science in this decisive period of social and scientific transformation.

Chapter 8

ANTECEDENTS AND CONSEQUENCES OF THE INDUSTRIAL REVOLUTION

8.1—*THE EARLY EIGHTEENTH-CENTURY PAUSE* (1690–1760)

THE original impetus that had created science in the Renaissance and carried it through the great outburst of the mid-seventeenth century seemed to falter and die away towards its end. Within a few years of the publication of Newton's *Principia* in 1687, indeed even before it was written, there was a perceptible slackening of scientific effort and dying away of curiosity. This dip in the curve of scientific progress was a general phenomenon and not merely confined to England, though naturally, because science had been so highly developed there in the early days of the Royal Society, it was most clearly to be seen there.

To some extent this pause might be ascribed to reasons internal to the scientific world. The prestige of Newton had turned science in a direction that was to be sterile for many years because of the very finished character of Newton's own work and the distance by which he surpassed his contemporaries. To a far larger extent, however, the slackening of scientific advance in England, and to a lesser degree in the rest of the learned world, was due to social and economic factors. The class that had started the seventeenth-century scientific drive, the gentlemen merchants who were then concerned with using new methods based on science in navigation, trade, and manufacture, had been succeeded by a new generation, wealthier, less enterprising and curious, and much more complacent. These, the first Whig aristocracy, found the most secure investment in land and an outlet for their speculative interest in such glorious gambles as the South Sea Bubble. The class that was to replace them in power, the rising but still small manufacturers who were later to create the Industrial Revolution, had not yet become conscious of the possibilities or even of the existence of science. They were occupying themselves

throughout the early part of the eighteenth century with developing and using improved technical methods, still for the most part hand operated, which served for a while to cope with the ever-increasing demands for cloth and manufactured articles.

These changes reflected themselves in the Olympus of science, the Royal Society; the impetus to serve trade withered away and the Society itself fell on some very lean days. Conrad von Uffenbach, who visited the Royal Society at Gresham College in 1710, writes of its collection of instruments as

> not only in no sort of order or tidiness but covered with dust, filth and coal smoke, and many of them broken and utterly ruined.

He continued:

> If one inquires after anything the operator who shows strangers around will usually say " A rogue had it stolen away," or he will show you pieces of it, saying " it is corrupted or broken "; and such is the care they take of things." [5.12a]

The society was in serious financial difficulties and an inquiry of 1740 showed that a large number of fellows had ceased to pay their subscriptions.[4.11]

Meanwhile, however, though science somewhat languished, technical change had not ceased, and if the advance in the early eighteenth century seems slow it is only in relation to the vast changes that were effected in a few decades by the Industrial Revolution. Some of these lines of change which were well under way in Britain during the early part of the century were to be of the utmost importance for the future both of industry and science.

One of these was the rapid improvement in agricultural practices. These improvements, adapted from those of the Dutch in the seventeenth century (p. 333), spread rapidly in Britain, and helped to make commercial farming pay. They were made possible on the one hand by the availability of capital, originally from mercantile sources, to invest in land, and on the other by the rapid growth of towns, in the first place of London, that provided a reliable market for corn, meat, and vegetables. Technically an advance, they were socially unjust and cruel, involving the ejection by Enclosure Acts of a peasantry with traditional but poor title to the land and with even poorer means of cultivating it.[5.38]

Another change of vital importance was the rapid expansion of a new heavy industry, based on coal, with improved mining and transportation methods, and of radically new methods of making iron and steel. Here one scientific development, the steam-engine, originally used for draining mines (p. 414), was of key importance, as was the technical development of making iron with coke from "pit" coal, instead of using the immemorial wood charcoal (p. 283), and which was first effected in an inconspicuous way by the Quaker Abraham Darby in 1709. These developments were, however, limited to what were the minor fields of industry, and did not amount in themselves to an industrial revolution, though they were its necessary precursors.

This phase marks the actual point of no return between the age-old country-based economy to one based on the coalfields; from an economy of food to an economy of power. In Patrick Geddes' terms it was passing from the era of *eotechnics* to that of *paleotechnics*.[5.34] This, however, is true only of the very growing points of the new technique, on and near the coalfields themselves. The radical changes were largely confined to Britain, though in the iron-making countries there was an independent development of machinery, as in the rolling and slitting mills of Polhammer (1661–1751) in Sweden[5.64; 5.10.635] and the use of a steam-engine for iron working by Polzunov (1758) in the Urals.[5.19]

The shift to a coal-based economy was not only to alter the balance between northern and southern England but also to be a major factor in the meteoric rise of Scotland as an industrial and intellectual power of the first rank.[5.4] Scotland, despite the antiquity of its traditions and the Calvinist movement of the sixteenth century, had not kept pace with the rapid development of England in the seventeenth. The resources for the early Industrial Revolution were lacking. The position was very different once the advantages of coal were realized. The very poverty of the country, combined with the high literacy and puritan traditions, meant that once the idea of improvement was accepted it would not be held back, as it had been in England, by complacency and ignorance.

Moreover, also due to Calvinism, Scotland had established an intellectual link with Holland, particularly with the university of Leyden, ensuring a steady flow of well-trained men, especially in medicine, which included chemistry. The great Boerhaave (1668–1738), a follower of van Helmont and

teacher of half the chemists of Europe, had a particular influence on Scotland, where his pupils took the leading part in introducing science to the universities. The universities of Scotland, in the eighteenth century, were indeed most unlike their English sisters; they became active centres of scientific advance which sought in every way to link practice to theory (p. 373).[5.44]

While Scotland and England were rapidly approaching the Industrial Revolution, the developments of even such an advanced country as France still continued along the old lines. There was a steady growth of handicraft industry of very high quality with considerable division of labour and an output greater than that of England, but there was no attempt to use large-scale machinery except for such purposes as royal waterworks.

Fashionable science in France: the Philosophes

Nevertheless, the same period in France saw a sudden rise of activity in science, though this rise was of a very different kind from that in England. It was essentially an expression of interest, on the one hand, of part of the rather bored aristocracy, not, as in England, occupied practically with its estates, but cooped up in court circles; and on the other, of a mode of expression of dissatisfaction with affairs on the part of a rising middle class, headed in France by the administrative and legal professions. Science was fashionable and revolutionary at the same time. It is symptomatic that the man who introduced Newtonian philosophy into France was none other than Voltaire (1694–1778).[5.54a]

Much of the effort of the amateurs of science—natural philosophers or *philosophes*—was spent on criticism of existing institutions which were felt to be cramping the economic and political development of the country. There was, however, an increasing interest in industry but, unlike in England, it came from above on the seventeenth-century pattern. Réaumur (1683–1757), for example, a man of great intelligence and wide interests, carried out from 1710 to 1720 a long industrial research on steel-making (p. 429). Because, however, they met with no response in a tradition-ridden industry, the results of his discoveries did not create a steel industry in France and their advantages were only reaped by English steel-makers more than a hundred years later.

The spread of science in Europe: Prussia, Sweden, Russia

It was also in this period that interest in science spread far more widely than to the group of countries of France, England, and Holland which had monopolized it in the seventeenth century. Academies on the English and French models were being set up in various kingdoms of Germany and Austria through the efforts of Leibniz, the universal philosopher; and later under the patronage of the eccentric, scientific, and poetical king of Prussia, Frederick the Great. By the middle of the century no court could be called complete without its Academy of Arts and Sciences in which academicians, usually rather irregularly paid, had to compete for princely favour by producing laudatory odes or amusing experiments.*

The northern countries of Sweden and Russia also marked their new military and economic importance by the setting up of academies. These were, however, to have from the outset a different function from the polite societies of the other European countries. They were concerned largely with the scientific study of the great raw material resources of wood, tar, and flax, of iron and other minerals, all so much needed on account of the rapid increase in sea-borne trade that those countries were just beginning to exploit. Peter the Great introduced science as one aspect of his design to create an economically and militarily independent Russia.[6.65] Though at first he had to staff it with foreigners, mostly Germans and French, but including a prince of mathematicians, the Swiss Euler (1707–83), he aimed at building up a truly national body of science. Success was not to come till after his reign with the life-work of that intellectual giant of the eighteenth century, Michael Lomonosov (1711–65), poet, technician, and physicist, the first of a succession of great Russian men of science (p. 448).[5.59; 5.73]

The establishment of science: the influence of Newton

It is not surprising, in view of these social and cultural changes, that the trends in science throughout most of the eighteenth century should be different from those of the seventeenth. In a more gentlemanly age the accent on the useful was not so stressed, though it was never absent, as Réaumur's and Hales' research show (p. 448), and it was to become more prominent than ever towards the end of the century. At the beginning, the entertaining and instructive side of science came more into prominence. There were no more

battles with the Churches, which, Protestant and Catholic alike, had lapsed into a tolerant indifference. In any case science had arrived; it was an institution, it had acquired its own internal tradition.

Thanks to Newton, mathematical astronomy was well established as the senior branch of science and it was steadily followed up throughout the century, more successfully in France than in its native England, where the great man's prestige was more paralysing. Nothing, in fact, of physical significance was added to the Newtonian theory, but the mechanical principles were generalized and were combined with a new mathematics due largely to Leibniz. This combination was to prove an instrument for solving the more intricate problems that arose later in the branches of physics, particularly from the study of electricity and of heat. The great generalizations of mechanics of Euler, d'Alembert, Maupertius, Lagrange, and Laplace were to be the basis of the mathematical–physical revolution of the twentieth century.

New interests: electricity and botany

Though these studies carried the full prestige of science, the immediately significant advances lay not in deepening but in widening its field of interest. The major contributions which were made to science in the early and middle eighteenth century were in the fields of *electricity* and *botany*, one an entirely new addition to science, the other a revival and a new formulation of almost the oldest of the sciences. Both, in their first stages, showed a definite trend away from the mechanical and mathematical bent of the seventeenth century into fields of greater variety and less rigour (pp. 431 f., 462 f.).

The study of electricity started as rather a pleasant and useless pastime and provided a series of new, exciting, and spectacular experiments. It was Franklin who, by his invention of the lightning conductor, literally brought electricity down to earth and forecast its future importance. Botany escaped in the eighteenth century from the care of the herb garden from which the doctors of medicine prepared their physic and, under the inspiration of Linnæus, spread everywhere into the wilderness, reinforcing the social tendencies of a bored aristocracy and a thwarted bourgeoisie to return to Nature.

With botany came a renewed interest in collections of all kinds—coins, minerals, fossils—very suitable for noblemen's

cabinets, later to blossom forth as new museums. The curators came to form a new group of scientists, ranging from wealthy and eminent Sir Hans Sloane (1660–1753) whose magnificent collections were the nucleus of the British Museum,[5.15] to the light-fingered Raspe (1737–94), who has the double distinction of being expelled from the Royal Society and writing Baron Munchausen's tales.[5.17]

The new order in philosophy

The early eighteenth century was predominantly a time for the digestion of and reflection on the enormous scientific advance of the seventeenth. The philosophers of the seventeenth century had the task of proving that an alternative existed to the classical–religious world-picture of the Middle Ages, and found it in the prophetic works of Bacon and Descartes, acclaiming the triumph of the new science. Those of the eighteenth century, on the other hand, could take the scientific world-picture which Newton had given them for granted. Their task was to extend it and to reconcile its findings, and still more its attitude of mind, with the new political and economic pattern that was beginning to appear in their own time.

At first they preached an attitude of acceptance to a new and rational order. Locke, himself a scientist and doctor, leaving little space for the supernatural, applauded the rule of law—the scientific law of Newton and the civil law established by the constitutional revolution of 1688. Leibniz, for all his mathematical and philosophic gifts and his pleas for European peace, was essentially a medieval thinker. He propounded the doctrine of "pre-existing order" little different from the Providence of the churchmen, and he applauded the fact that "everything was for the best in the best of all possible worlds." [5.59a]

Nevertheless, this world would not stay still. The succeeding philosophers felt there was something wrong with this complacent picture. The idealist Irishman, Berkeley, in the interests of established religion, denied the reality of the world and of science except in the eye of God. This produced little effect in his time but was to become a basis of reaction in the twentieth century. The sceptic Hume was much more successful in proving that we could know nothing with certainty, including particularly the dogmas of religion. The cynic Voltaire went further and led the attack on the Church itself in

the name of reason and benevolence. As the century wore on philosophy was tending to occupy itself more and more with social and economic reform and to pave the way for the French Revolution (pp. 725 f.).

8.2—*SCIENCE AND THE REVOLUTIONS* (*1760–1830*)

The second phase of our period covers seventy years as decisive in science as they were in politics. Comparable to the seventeenth century in its scientific importance, it far exceeded it in its immediate and in its practical consequences. It includes the Industrial Revolution in Britain and the political revolutions in America and France. The revolutionary wars in effect divide it in two, though they do not cut the continuity of science and technique. The first forty years, 1760–1800, witnessed all these events and also the onset and consummation of another revolution in science, the pneumatic revolution, which, linked with the discovery of the production of the electric current, was virtually to create a new and rational chemistry. The second part of the phase, from 1800 to 1830, though not so fruitful in new scientific or political ideas, remained one of immense vigour and expansion in all fields of practical human activity.

The connection between these different aspects of social change cannot have been a chance one. Indeed, the more closely they are examined the more intricate appear the threads knitting science, technique, economics, and politics together at this time into one pattern of transformation of culture. The period is a crucial one for the development of humanity. It was then and only then that the decisive turn was taken in man's mastery of Nature in the double substitution of multiple mechanisms for the human hand and of steam-power for the weaker forces of man and animal and the inconstant and localized forces of wind and water. The two basic transformations of the sixteenth and seventeenth centuries which made those of the eighteenth possible were the birth of experimental quantitative science and of the capitalist methods of production. At the time when they occurred they still remained largely separate.[4.64] The major practical use of and stimulus to science had been in the field of navigation, an indispensable adjunct to trade but only indirectly connected with production. Very little of immediate practical use came of the great and deliberate

effort of the scientists of the seventeenth century, newly banded in their Societies and Academies, to improve manufactures or agriculture (pp. 313 ff.). By contrast the later eighteenth century was to see the coming together of the scientific and the capitalist innovations, and their interaction was to set loose forces which were later to transform capitalism and science and with them the lives of all the peoples of the world.

Although there is ample material and even adequate analysis of the political, the economic, the technical, and the scientific transformations of the eighteenth century, these studies have remained largely separate and the combined analysis of them has yet to be written. It would be impossible to embark on it here; the best that can be done is to attempt to put the scientific development in its place against the economic and political background and to trace how far it was affected by, and itself in turn affected, the other aspects of contemporary society.

The Industrial Revolution

The " Industrial Revolution " is the name that Engels was apparently the first to give it as far back as 1844,[5.30] though it was later sanctified by Toynbee.[5.91] Nothing less than the term revolution can be used for the change of productivity in those fields of manufacture in which it first arose. The output of cotton goods rose five-fold between 1766 and 1787.[5.14a*] The consequent effects on trade, agriculture, and population were as definite and almost as rapid. Wherever its influence touched a new country, this was marked by a sharp upward break of earlier production trends.

The Industrial Revolution was closely limited in its place of origin; nearly all its major developments occurred in central and northern Britain and mostly in the near neighbourhoods of Birmingham, Manchester, Leeds, Newcastle, and Glasgow. Though the event itself has all the characters of an explosive process set off by a particular combination of circumstances that determined the place and time of its occurrence, it remains the final phase of a sustained increase in production over the preceding seventy years or more. Economically this seems to have been determined by the steady growth of a market for manufactured products, mainly textiles, itself largely a consequence of the extended navigations and colonial developments of the seventeenth century.

Coal and iron

The combination of economic and political preconditions for a radical change in production specially favoured Britain. It was there rather than in France that manufacture could develop freely to meet the demand, for both feudal and royal restrictions had been swept away by the revolutions of the seventeenth century. The other peculiar advantage of Britain was, paradoxically, the shortage of wood, the basic fuel as well as the basic structural material of all previous civilization. It was this that had forced the development of the use of the inferior, but far cheaper, *coal* for fuel and later of the more expensive but far better material *cast iron* for structures (p. 283). Their production rapidly increased in the later eighteenth century and both engines and mining and metallurgical methods were vastly improved, thanks in part to a new impetus from science marked by such men as Roebuck, Black, Smeaton, and Watt (p. 417). So also were methods of transport, particularly canals.

The mechanization of the textile industry

The Industrial Revolution itself did not find its origin in developments in heavy industry and transport; it came and could come only from developments within the major industry of the country, and indeed of all countries up to that time: the textile industry. As both the internal and foreign demand for cloth increased, the old merchant and guild-bound industry of southern England could not expand rapidly enough and low wages and freedom from restrictions drew it northwards. There, first in Yorkshire [8.16] and then in Lancashire, it found added advantages in water-power for processes such as fulling, and coal to help with the washing and dyeing. By 1750 the industry came to deal with a new fibre, cotton. Cotton cloth had been imported from India. When this was prohibited at the instance of the clothiers there was a great urge to make it at home. Raw cotton could be grown in the new American plantations. But cotton called for new techniques and was not bound by the old traditions of wool. It was first worked up in the poor district of Lancashire, eminently suitable on account of its damp climate. There, the demand for yarn soon outran the capacity of the old hand-spinning.

There had been isolated attempts at the use of machinery in the textile trade (Fig. 11), and even of power-driven machinery, such as that of the stocking frame and of Lombe's silk mill in 1719.

They had succeeded but not spread, as they had only a limited market to supply. Here, at last, in the cotton industry, was unlimited scope to substitute machinery for hand work. The great inventions, Hargreaves' spinning jenny of 1764, Arkwright's water-frame of 1769, and Crompton's mule of 1779, made the first real breach in the old hand techniques, first by multiplying the action of the hand and then by the use of power in the primary process of spinning.[5.10.508] The relatively enormous output of these machines led to their extension on such a scale as to stretch the capacity of the small streams that drove the mills, and in 1785 the last logical step was taken when Watt's steam-engine was adapted to drive them.

Industrial capitalism

The textile revolution, which was later to spread to the weaving side with Cartwright's power loom of 1785, and to include wool and linen as well as cotton, was by no means only a technical one. It was made possible only by the social and economic changes of the early eighteenth century and was itself to give rise to the even greater changes of the nineteenth. To enable the revolution in production to begin, a priming of both *capital* and *labour* was required, for each of these in their modern form had come into existence in this period. Capital was derived in the first place from the great merchant profits of the preceding century, which had begun to skim the resources of the newly-discovered lands in mines and plantations, both worked by slaves, or from the almost undisguised loot of India.[4.3] Labour had to be liberated from the land through the enclosures and, as it was no longer cramped by the guild restrictions of the medieval towns, it had to work long hours for low pay in the mills. At first there was not much of it, hence the incentive to labour-saving machinery, particularly such as could be worked by the unskilled, especially women and children.[5.37] Later, with more drastic enclosures and with the importation of poor Irish, there was labour enough and to spare, and the rush of radically new inventions was replaced by an enormous extension of those already in existence, improved but not transformed.

Concentration of industry

The market for textiles determined the outbreak of the Industrial Revolution in the particularly favourable circum-

stances which then obtained only in Britain. At one remove the market for textile machinery and textile processing stimulated the iron and chemical industries, while all of these called for an ever-increasing supply of the universal provider, coal, which in turn provoked new departures in mining and transport. By the mid-century, thanks to Darby's invention, cast iron was available in quantity. The shortage was now in wrought iron, and here the need was met for the time being by Cort's method of puddling introduced in 1784. The scientific and technical aspects of these changes will be discussed later (p. 429), but here it is essential to point out again that they ended the age-old dependence on wood as a raw material and brought the iron industry from the forests to the coalfields, where so much other industry was already concentrated (p. 284).

Concentration, indeed, was a prime feature of the Industrial Revolution. Feudal domestic industry, and even urban guild production, was necessarily scattered over many counties. The new mechanical industry hugged the coalfields from the very start. The new industrial towns—Manchester, Birmingham, Newcastle, and Glasgow—accounted between them for nearly all the new products.* These great and growing manufacturing towns, however, exerted their influence far and wide, on one side by their products, the cheapness of which destroyed domestic industry wherever they reached, on the other by their need for hands and for food.[5.1; 5.2; 5.8; 5.37]

The agricultural revolution

It was this demand that encouraged the new cash-crop agriculture of the landlords and farmers, who were replacing the peasants and their subsistence agriculture over most of England. The agricultural revolution was a mixture of empirical breeding and crop rotation and mechanization with the beginnings of drill ploughs, horse harrows, etc.[5.10.501] It had been prepared by a few enterprising improvers in the early eighteenth century, drawing on Dutch experience, but did not get under way until industry had created a new market for corn and meat and had, as well, provided first the tools and then the power to carry it out. In itself it marks as radical a change in human affairs as the Industrial Revolution. As it advanced, less and less labour was needed on the farm to produce food, which reinforced the tendency to draw the bulk of the population into the cities. Beginning in England, mechanized agriculture was soon to

spread to the newly opened lands of America and then, many decades later, to the more populous agricultural parts of Europe.

Interest in agriculture was not limited to temperate zones. The search for tropical products and possible colonies led to further voyages of discovery. These were no longer the semi-piratical ventures of the seventeenth century, like those of Dampier, but properly equipped scientific expeditions in which many nations engaged in polite rivalry. Cook (1728–79), Bougainville (1729–1811), and La Perouse (1741–88) are the most noted examples. Even the ill-fated voyage of the *Bounty* in 1789 was undertaken with the object of introducing bread-fruit trees from the South Seas into the West Indies.[8.74]

The creators of the Industrial Revolution

The Industrial Revolution itself did not, in its first stages, depend on any contribution from science; its architects were artisan inventors whose success was made possible by exceptionally favourable economic circumstances. The central developments of textiles did, in fact, occur without the application of any radically new scientific principle. Their real importance was that they marked the emergence of a new social factor in action. The workman with his small accumulated or borrowed capital was here, for the first time, establishing his claim to change and direct the processes of production, in "the truly revolutionary way," as Marx called it,[4.3.123] as against the mere domination by a merchant of the production of small artisans through the putting-out system.

Steam-power

Nevertheless, in default of the steam-engine and the virtually unlimited power it provided, the Revolution might have gone no further than speeding up textile manufacture in well-watered districts such as Lancashire and the West Riding of Yorkshire, and have achieved little more than had the analogous technical achievements of China many centuries before. It was the use of the steam-engine for power in the textile industry that joined together the two originally separate strands of heavy and light industry and created that modern industrial complex that was to spread from its origin in Britain all over the world. Now the steam-engine, as will be shown later (pp. 414 f.), is pre-eminently a conscious application of scientific thought, and to that extent science played an essential part in the Revolution.

In return the Industrial Revolution itself was to stimulate and support a new outburst of scientific activity. This was even more closely linked with the problems raised by industry than those of the seventeenth century. Not only in England, Scotland, and France but, as the century wore on, in Russia, Italy, and Germany as well, the movement towards a conscious utilization of science " for the improvement of arts and manufactures " spread among the newly risen bourgeoisie, and was even smiled on by a section of the aristocracy and the benevolent despots such as Catherine the Great and Joseph II of Austria. But the interest was different from that of the century before; it was more solidly related to achievements in production and it carried a revolutionary flavour.

Science in industrial areas: the "Encyclopédie"

It is characteristic that the scientific revival of late eighteenth-century Britain should come no longer, as in the seventeenth century, from Oxford, Cambridge, and London, but from Leeds, Glasgow, Edinburgh, and Manchester, and most of all from the new town of Birmingham, which became its most celebrated centre (p. 373). In France, where the analogous process was more and more obviously held up by an out-of-date political and social system, the energy of all advanced minds, in despair of any improvement, ultimately turned to getting rid of it, an effort which contributed to the French Revolution. Its monument is the great *Encyclopédie des Arts, Sciences et Métiers* published in twenty-eight volumes from 1751 to 1772 thanks largely to the labours of Diderot (1713–84) and D'Alembert (1717–83), but in which nearly all the *philosophes* took part. This was the bible of the new liberalism, uniting free thought with science, manufactures, and *laisser-faire.*

Benjamin Franklin

The most eminent prophet and forerunner of the new movement was Benjamin Franklin, of whom, far more truly than of Canning, it can be said that " he brought in the New World to redress the balance of the old." He was born in 1706, the son of a poor tallow-chandler in Boston, USA. He was apprenticed to a printer and publisher at the age of twelve and ran away to Philadelphia at seventeen to set up on his own. He was sent on a wild-goose chase to England, where he maintained himself as a printer and managed to acquire a thorough

knowledge of contemporary science and politics. In 1726 he returned to Philadelphia, laid the foundations of electrical theory, and invented the lightning conductor, the rocking chair, and the iron stove. In 1743 he founded the first American Philosophical Society. He became Postmaster-General of the colonies and equipped the ill-fated expedition of General Braddock against Fort Duquesne (Pittsburgh) in 1755.

Later he returned to England as agent for Pennsylvania and there realized that he had no option but to work for the independence of the colonies, which the aristocratic oligarchy of Britain could neither appreciate nor govern. He was indeed the first to understand the potentialities of the New World and to start planning for its future, as his work on the Declaration of Independence and the Constitution bear witness. Too old to fight in the War of Independence, he rendered his last, and in some ways greatest, service to his country as ambassador to France, securing the support which proved decisive in that struggle. It was during his stay in Paris and Versailles that he exercised the greatest influence on the direction of politics and science. Franklin was the Bacon of the eighteenth century; but a Bacon with a difference—no longer the wily courtier or learned judge appealing to princes to establish science, but the man of the people born in a freedom that he was determined to preserve and enlarge. He was in the forefront of science in the new age. He joined heartily in the designs of the *philosophes* and added to them the flavour of democracy and practical common sense which they had lacked.

The dissenting academies and the Lunar Society

Franklin's younger contemporaries in Britain carried his ideas into practice. Although, as has been explained, the Industrial Revolution owed little to science, the men who directed its progress were thoroughly imbued with the scientific spirit. The value of science, now less appreciated at court or in the city, was fully grasped by the generation of northern manufacturers and their friends. They saw that the reason why science had not been successful in the past was because its adepts had not been practical men. Further, for the first time outside the navigation schools, it began to be taught systematically. Despite the neglect of the older universities (barred in any case to dissenters, as most of the new men were) it found a place in the dissenting academies, such as those of Warrington

and Daventry. Independent foundations, their success was a measure of the need felt for science, and during the eighteenth century they provided, next to the Scottish universities (p. 360), the best scientific education in the world.

It was in this period, far more so than later in the nineteenth century, that the manufacturers, the scientists, and the new professional engineers mixed together in their work and social life. They intermarried, entertained lavishly, talked endlessly, experimented and associated in new projects. This was the age of the "Lunar Society" of Birmingham and the Black Country which used to meet at members' houses on full-moon nights and counted among its members John Wilkinson (1728–1808), the ironmaster who lived and dreamed iron and was buried in an iron coffin; Wedgwood (1744–1817), the potter; Edgeworth, the genial Irishman full of wild and noble-minded projects for social improvement; the serio-comic radical Thomas Day of "Sandford and Merton"; [5.75] the poetic but practical Dr Erasmus Darwin (1731–1802) of Lichfield; Joseph Priestley (1733–1804), of whom more later; the melancholy, indefatigable Scotsman James Watt (1736–1819) [5.26] with his younger compatriot, Murdock (1754–1839), the inventor of coal-gas lighting; and finally, the heart and centre of the whole movement, the wealthy, enterprising, jovial, and hospitable Matthew Boulton (1728–1809),[5.27] the Birmingham button-maker who became, as the first manufacturer of steam-engines, almost literally the prime mover of the Industrial Revolution. As he wrote to the Empress Catherine, "I sell what the whole world wants—power."

Closely linked with these by personal ties was the more serious group of the Scottish renaissance of the eighteenth century: the philosopher Hume (1711–76), who provided a link with the *philosophes* of France; Adam Smith (1723–90) with his *Wealth of Nations*, the intellectual father of *laisser-faire* capitalism; Dr Black (1728–99), the originator of the pneumatic revolution; [4.69] Dr Hutton (1726–97), the founder of modern geological theory.[5.35] Others, like Dr Roebuck (1718–94), a medical man turned chemical manufacturer and founder of the Carron Works, the first deliberately planned iron-works, and Dr Small (1734–75), the tutor of Thomas Jefferson, belonged equally to England and Scotland.

Such a combination of science and manufacture was only to be found in the Britain of the late eighteenth century. Its

existence marks a period of dynamic equilibrium of technics and science, a transition between a period in which science had more to learn from industry than to give to it and one where industry came to be based almost entirely on science. The interests of corresponding circles in other countries were necessarily more economic and political, for they lacked the solid basis that only the new manufacturers could give. Britain appeared to them as a kind of industrial Mecca and indeed some of the best accounts of British industry come from intelligent foreign visitors, such as Gabriel Jars (1732–69), one of the founders of French heavy industry. It is interesting to note that when it was decided in 1782 to start modern iron-working at Le Creusot, the first large works outside Britain, from which not only the French but also the German steel industry are derived, it was necessary to take in W. Wilkinson, the brother of the ironmaster, to cope with the technical side.[5.17a]

Rational chemistry and the pneumatic revolution

The great new scientific contribution of the period of the Industrial Revolution was the foundation of modern, that is to say, rational and quantitative chemistry. This was an event in the history of science of an importance ranking with the great astronomical–mechanical synthesis of a century before. How it occurred will be told in the next chapter; for the moment it is sufficient to say that it marks the result of the rapid development of the chemical industry, largely as an ancillary to the new large-scale mechanical textile industry, and of the consequent interest of scientists in the problems of matter and its transformations.

The actual clue which made possible a simple explanation of the complexities of chemistry was the study of the new gases, itself closely linked with the experiments on air and vacuum of the previous century and with the development of the steam-engine of its own time. Indeed the rise of chemistry may well be called the result of this "pneumatic revolution." As a result of the work of pioneer experimenters such as Black in Scotland, Priestley in England, and Scheele in Sweden, the logically trained mind of Lavoisier brought order into the chaos of old and new facts. Twenty years later Dalton provided an explanation in terms of atoms which securely linked chemistry into the Newtonian material–mechanical scheme, though an-

other hundred years had to pass before the nature of the forces between the chemical atoms could be explained (pp. 448–53).*

The Age of Reason: Joseph Priestley

The effects of science were not limited to the industrial field. Beginning with Franklin, the scientists of the later eighteenth century were predominantly, in England as well as in France, radical and liberal in their ideas. The most characteristic figure of this movement which combined the pursuit of science, philanthropy, and radical politics was Joseph Priestley (1733–1804). Son of a Yorkshire cloth dresser, he was educated at the dissenting academy at Daventry with a view to becoming a Congregationalist minister. He drank avidly the new spirit of enlightenment, which did not lead him to infidelity, as it would have done in France, but to a rational Christianity of a more and more Unitarian kind. This did not recommend him to the orthodox, but his learning and interests brought him in contact with the scientific world and particularly with Benjamin Franklin, who inspired him to write a *History of Electricity*,[5.67] which started him on his scientific career. In 1767 he became a minister at Leeds, where he carried out his experiments on carbon dioxide (p. 449). From then on he received the support of manufacturers and some liberal noblemen. He was, in fact, for the most fruitful period of his life, 1773–80, provided with a house and laboratory by Lord Shelburne. It was there that he made his discovery of oxygen which brought him international fame.[8.24]

Nevertheless for him these scientific pursuits were subsidiary to his main purpose of doctrinal controversy in favour of liberal religion. Priestley's religious views were closely linked with his science. Far from wishing, as Descartes had done, to separate matter and spirit, reason and faith, he sought a pure revelation that would unite them. This revelation he sought equally in scripture and in Nature as the work of the divinity. To his mind the activities revealed by electricity showed matter not to be inert and therefore not intrinsically incapable of sensation. In one sense his thought reaches back to the hylozoism of Erigena (p. 214); in the other, forward to the organismal philosophy of Whitehead. He regarded as *Corruptions of Christianity* [5.9.190] such beliefs as those in the Trinity, the Atonement, predestination, and even the existence of the soul. In the eighteenth century such views had a limited

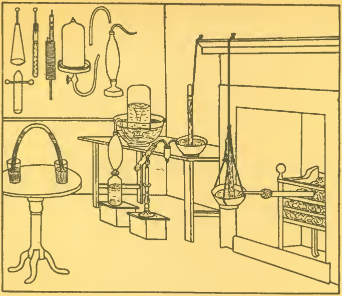
appeal. The French were surprised to find a philosopher who believed in God; the English found Priestley's religion difficult to distinguish from Atheism. Yet he firmly believed in Christian morals, " which are none other than the well-known duties of life, greater piety towards God, greater benevolence to man." It was in this spirit that Priestley supported every form of social and cultural improvement, tending in his words to " the greatest happiness of the greatest number."

He never took an active part in politics, but, at a time when opinion was hardening against the tendencies of the French Revolution, merely to disagree publicly not only with the doctrines of the Church of England, as by Law established, but also with those of respectable dissenters, was considered tantamount to rebellion if not treason. The gentle and benevolent Dr Priestley soon became a radical republican bogy man. The climax came in 1791 when a Birmingham mob, in defence of Church and King and with the connivance of the authorities, burnt down his house near that city, involving the total loss of his library and laboratory. Even when safe from violence he found himself so shunned by his colleagues for his political views that he emigrated to America, where he died in 1804. Events seemed to have made his immediate mission a failure, yet directly or indirectly his influence was to rise again to inspire the liberal and philanthropic movements of the nineteenth century (pp. 387, 731 f.).

Antoine Laurent Lavoisier

Priestley's name is indissolubly linked in the history of science with that of Lavoisier, for it was on the basis of the Englishman's pioneer researches that the Frenchman erected the revolutionary theory that was to make chemistry once and for all a rational and quantitative science.[5.52] As a personality Lavoisier dominated late eighteenth-century French science. He was a very different man from Priestley. Though, for both, science was only one, if the main, interest in their lives, there was nothing in Lavoisier that corresponded to the vague religious, radical philanthropy of Priestley. Instead the concern of Lavoisier was with efficient public service and the practical use of science to bring the *ancien régime* up-to-date. Lavoisier showed himself from youth as an extremely competent and confident man. In part this was because he was born rich, the last of a family that had risen step by step through care and good management

a



b

FIG. 12.—EIGHTEENTH-CENTURY TECHNOLOGY AND SCIENCE

(*a*) Priestley's laboratory.

Essentially for the preparation and handling of gases. Note the domestic nature of the apparatus. A candle is used for mild heating, the coal grate for strong (p. 449).

(*b*) Newcomen vacuum steam-engine.

Note the operator who has to open and close valves at each stroke. Later this was replaced by valve gear (p. 415).

from postilion to postmaster, to merchant, to notary, to attorney, to the *Parlement* of Paris. Lavoisier himself was to take the final step, short of nobility, and buy a place in the *Ferme Génerale*, the small and immensely rich corporation that collected taxes for the king. He could not foresee that it was to cost him his head.

His scientific education was of the best and included mathematics, astronomy, botany, anatomy, geology, and, most important of all, chemistry, under Rouelle (1703–70), the genial demonstrator of the *Jardin du Roi*. Here was a young man of ample means, an easy master of all available knowledge, with an ambition to reduce both science and society to some reasonable order. He undertook his first scientific effort when in 1767, at the age of twenty-four, he went on a tour of France to draw up a geological map and make a survey of its mineral resources. Later he was to be occupied with such problems as the system of street lighting, experimental farming, and many other projects of general improvement as characteristic of the eighteenth century in France as in Britain. Most important of all was his apointment in 1775 to the Gunpowder Committee and his establishment in the Arsenal, where he set up what was probably the best laboratory for the time in the world—Priestley's laboratory could be carried on a tray (Fig. 12).

Of Lavoisier's scientific work we shall write later (pp. 450 ff.); here we are concerned with him as an influence in the utilization of science, in which he displayed a mastery that was not to be equalled for many years. In everything he did he showed the operation of an exceptionally clear, orderly, and dominating mind. He was not given to philosophy. Though he opened the vast realm of chemistry to the application of physical and mathematical principles, it was the actual illumination he brought rather than his methods that remained. His prosecution together with the other Farmers General was not directed against him personally, still less against science. He suffered for the system with which he had been inevitably and conspicuously identified in the movement of a revolution that ironically he had done so much to further.

Priestley and Lavoisier were only two individuals who typified the upsurge of hope and progress so closely linked with the rapid growth of science and industry. Towards the end of the century more and more men, and, for the first time in history, women too, began to think of the possibility of a world ruled by

reason and equality and not by prejudice and privilege. This movement spread widely through Europe and the New World, through Italy, Austria, Prussia, Russia, even to Spain. It is noticeable, for instance, how at this time science, long dormant in Italy, showed a revival of the national genius, as the major contributions of Galvani, Volta, and Avogadro show. They were influenced not only by doctrines evolved from their own experience and aspirations, as in the works of J. J. Rousseau (1712–78), but also by everything that was being learned of the eminently reasonable society of the Chinese, of the virtuous society of India, of the noble Redskins, and by the reports of the scientific expeditions on the simple and happy life of the peoples of the coral islands in the South Seas. Society wisely ordered by philosophers and free from the despotism of custom became the ideal, and everything pointed to a return to Nature (p. 725). It was the era of enlightened despotism, of Frederick the Great, Joseph II, and the great Catherine. Science was one of its major inspirations. It furnished at the same time a new intellectual tool for criticizing the old régime and a means for the practical regeneration of mankind through the use of mechanically transformed industry. It was to liberate an enormous scientific and technical outburst which, in its intensity and its consciousness as well as its high level, produced a greater effect on society than anything that the world had seen before.

8.3—*THE FRENCH REVOLUTION AND ITS EFFECT ON SCIENCE*

The French scientists of the last days of the monarchy were deeply imbued with the improving spirit of the *philosophes*—the new régime gave them their chance. In the general sweeping away of feudal vestiges and in the exaltation of reason the new science played a leading role. All the revolutionary governments formally recognized its importance, gave much to science and expected as much from it. Some scientists, like Monge (1746–1818) and Lazare Carnot (1753–1823), were ardent republicans and immediately took charge of economic and even military administration. Others, like Bailly (1736–1793), Condorcet (1743–94), and the great Lavoisier, though at first they co-operated fully, could not live down their association with the old régime and were victims of the popular

reaction to the invasion of France. The majority occupied themselves with the reform of the antiquated machinery of State and of education on scientific lines.

The first task was the reform of weights and measures and the establishment of the metric system, finally achieved in 1799. It needed a revolution to bring it about, as witness the persistence of the old cumbrous systems wherever the influence of France and French logic did not penetrate. The second great task was the creation of modern scientific education, the first real educational change since the Renaissance. The revolutionaries built systematically on a large scale on a foundation that had already been laid in the dissenting academies of England and in the military schools in France, despite the opposition of the old universities. Scotland was an exception; as we have seen, the Scottish universities were from the first in the foreground of scientific advance. Among the products of the dissenting academies were Priestley and Wilkinson the ironmaster—of the French military schools, the mathematicians Monge and Poncelet, and soldiers like Napoleon and, rather surprisingly, Wellington, after he left Eton. For industry and for war science had become indispensable. The foundation of the École Normale Supérieure, of the École de Médecine, and of the greatest of all, the École Polytechnique, gave models for the scientific teaching and research institutions of the future.[5.84] By choosing only the most eminent men to teach in them they created the type of salaried scientist professor that was, throughout the nineteenth century, gradually to replace the gentleman amateur or the patronized client scientist of earlier times.

The first crop of students of the new educational institutions contained such names as Charles (1746–1823), Gay Lussac (1778–1850), Thenard (1777–1853), Malus (1775–1812), and Fresnel (1788–1827), who were all destined to make significant advances in many sciences. These institutions gave opportunity to the gifted of all classes to gain a footing in science. It is to them that France owed her scientific predominance in the world, which lasted till well into the nineteenth century, until Britain and Germany were to follow her example in providing scientific education.

Napoleon: patron of science

The Napoleonic period, which followed close on the Revolution, did not lead to any slackening of the scientific drive.

Although the benevolent despots had patronized science, Napoleon took personal charge of its administration. He often attended sessions of the Académie, took a whole scientific expedition with him to Egypt, and was pleased to order the Abbé Haüy (1743–1822)—the founder of crystallography—to write a text-book on physics. He was, after all, the first ruler and the only important one for more than a century with a scientific education. He had therefore some idea, if only a shrewd bourgeois one, of its utility and saw to it that it gave practical support to his régime and to his armies.

The Napoleonic Wars had indirectly a considerable importance for science. The Industrial Revolution was only slowly penetrating France by the turn of the century, but France was a far more populous country than Britain, some 28 millions as against 11 millions, and its industrial output, though less concentrated, was actually greater.[5.45.3] It was therefore quite capable of maintaining the unprecedented strain of sending its armies to fight all over Europe. The British blockade, made possible by technical naval superiority, had little damaging effect at the time—its long-term effect was mainly to destroy France's overseas markets. Where it was felt, in cutting off supplies such as soda and sugar, it promoted the French chemical industry and helped to give France chemical predominance for thirty years. Unlike the wars of more modern times, the Napoleonic wars did not extend into the field of science itself, but served rather to promote the meeting of scientists of different countries. Napoleon awarded a prize to Davy for his electrochemical discoveries in 1808, and Davy did not hesitate to go to Paris to take it and protested against the small-minded people who objected merely because the countries were at war.[5.5]

The developments in Britain in the period of the French Revolution were very different. There, instead of vigorous and drastic innovation, there was an almost desperate clinging to the old forms of Church and State and a rejection of the liberalizing tendencies of the Whigs. Religious dissent turned from rational deism to emotional Methodism. None of these, however, interfered with the march of industry, provided with greater markets as a result of the blockade of France and the additional urge to produce war materials not only for Britain but also for its industrially backward allies.

The Royal Institution: Count Rumford

Only one effort was made at all analogous to the establishment of the new scientific schools of the Continent: the foundation of the Royal Institution in 1799. This was on the initiative of Sir Benjamin Thompson (Count Rumford of the Holy Roman Empire) (1753–1814), an American Tory, but with the same practical bent as Franklin. An opponent of democracy, he saw the need of efficient public service if the old régime was to survive, and demonstrated it by his management of the Kingdom of Bavaria before it was overrun by the French. There he drove the beggars off the streets and put them into workhouses; investigated economical methods of cooking so successfully that they could be fed for three farthings a day; and turned the army budget from a loss to a profit by devising industries for the soldiers. In the course of this he discovered the laws of transmission of heat and demonstrated how it could be generated by work. Returning to England he saw at once that the Industrial Revolution could not be a success unless there was some means of training a new type of mechanic who could base himself on science instead of blind tradition. For that he persuaded the wealthy to put up the money for an institution under royal patronage for:

> . . . diffusing the Knowledge and facilitating the general Introduction of useful mechanical Inventions and Improvements, and for teaching by Courses of Philosophical Lectures and Experiments the applications of Science to the common Purposes of Life.

It did not long preserve its founder's intention. Its first director was the great scientist but even greater snob and showman, Humphry Davy (1778–1829).[5.5] Davy is best known for his invention of the miner's safety lamp in 1815, a piece of direct industrial research which he undertook without fee. Though intended to prevent fire-damp explosions it was used effectively to work previously inaccessible gassy mines, so that output went up while the number of accidents remained about the same. Davy's pæan in favour of the utility of science in his introductory discourse of 1802, given when he was only twenty-three, well expressed the spirit of the new age. In it we find the following expression of the nineteenth-century credo:

> The unequal division of property and of labour, the difference of rank and condition amongst mankind, are

> the sources of power in civilized life, its moving causes, and even its very soul.[5.5]

With the combination of science, utility, and sound Tory sentiments, it is not surprising that the Royal Institution became a fashionable centre, as popular as the opera with the nobility and gentry.

To make it more exclusive, even the back door, by which the mechanics had been allowed to climb unobserved to the gallery, was bricked up. But it prospered and provided a unique subsidized laboratory in which a large proportion of the basic scientific discoveries of the first half of the nineteenth century were made. Its teaching was confined to public lectures, and though these attracted one of the greatest scientists of all time, the bookbinder's apprentice, Michael Faraday (p. 438), who was taken on as Davy's assistant and learned his science there, there was no place for hundreds of potential Faradays whom the England of that time could certainly have produced in as great a profusion as France.

The post-Napoleonic reaction

The great movement of the Enlightenment foundered for a time in the reaction that followed the Napoleonic wars—which had, in their earlier stages, done so much to spread the movement throughout Europe—and in the serious slump that followed in the 1820s. It was in such circumstances that the Industrial Revolution showed its ugliest side of unemployment and pauperization, and the ruling classes, with the spectre of another revolution before their eyes, felt obliged to use material and spiritual forces to the utmost to hold down the mob. Men's eyes turned backwards to a somewhat synthetic "Middle Ages," and a sentimental romanticism took the place of a rational materialism with its irreligious and revolutionary associations. There was a temporary decline of interest in science except in Germany, where science was linked with awakening nationalism and the windy transcendental *Naturphilosophie* (p. 469). The industrial need for science was dormant because of the drop in war orders; and there was less need of it than ever in the administration of the Restoration in France and the Holy Alliance. Nevertheless, this decline was only relative to the enormous activity of the last two decades of the eighteenth century. So much had been done then that

science was too deeply entrenched in the new industries for this recession to be either as severe or as long as that at the beginning of the eighteenth century. Nor was the spirit of science easily quelled. In Britain, France, and Germany, despite reaction, scientists and admirers of science formed the spearhead of the renewed movement of liberal reform.

8.4—*THE CHARACTER OF SCIENCE IN THE INDUSTRIAL REVOLUTION*

The seventy years from 1760 to 1830, and particularly the thirty from 1770 to 1800, are a decisive turning point in world history. They mark the first practical realization of the new powers of machinery in the framework of a new capitalist productive industry. Once these steps had been taken the enormous extension of industry and science of the nineteenth century was inevitable. The new system was so much more efficient and so much cheaper than the old that no serious competition was possible. Nor henceforth could there be any turning back. Sooner or later the whole pattern of life of every human being in the world was to be changed. The critical transition came as a culmination of changes in technology and economics which reached, as has been shown, a breaking point in Britain, on the technical side, around the year 1760, and in France, on the economic and political side, thirty years later. The changes were not easily effected; it was no accident that the period was one of unprecedented revolutions and wars.

In science, also, the eighteenth-century changes were revolutionary—the term pneumatic revolution covers only one aspect of them. Though they appear in conventional histories of science only as an appendage to the Copernican–Galilean–Newtonian rejection of ancient science, this is only a measure of how the historians themselves are still hypnotized by the classical tradition. The seventeenth century had solved the Greeks' problems by new mathematical and experimental methods. The eighteenth-century scientists were to solve by these methods problems that the Greeks had never thought of. But they were to do more: they were to integrate science firmly into the productive mechanism. Through power-engineering, chemistry, and electricity, science was to be henceforth indispensable to industry. The first step had been taken

in the seventeenth century with the contributions of science to astronomy in the service of navigation. Nevertheless, science still remained largely what it had become in classical times, a somewhat esoteric part of the framework of belief erected in the interest of ruling classes: it was part of the ideological superstructure. Effectively, it had contributed nothing to industry. Now, in the dawn of the nineteenth century, without losing its academic character, it was to become one of the major elements in the productive forces of mankind. This, as we shall see, was to be a permanent feature of growing importance destined to outlast the social forms of capitalism which had assisted at its birth.

In the field of ideas the age of revolutions gave little of importance comparable with that of the scientific discoveries or technical inventions of the period. Time was needed to digest the events and transformations that followed each other in rapid succession from 1760 to 1830. In thought the era lies, as it were, on a watershed. The ideas that inspired the revolutions were those of the French *philosophes*—of Voltaire and Rousseau. They were the heritage of Newton and Locke, based on emotional belief in man and on his perfectibility by free institutions and education once the shackles of Church and King had been loosened. Their German echo was to be found in the profound meditations of Kant (1724–1804), who attempted to weld in one system the achievements of science and the inner light of conscience (p. 735).

The ideas that were to come in the nineteenth century were based on the hard experience of the Industrial Revolution and the reluctance of men of culture and property to apply the watchwords of liberty, equality, fraternity too literally. The attempt to apply the social philosophy of the Enlightenment in the French Revolution had revealed serious limitations. It brought out particularly how little the new ideas concerned the lives of the peasants and poor workmen who made up the mass of the population. It was they—the *people*—who had given the Revolution its drive, but when its immediate objects—the abolition of feudal restrictions on private money-making—were achieved, the same people became the *mob*, a threat permanently suspended over the owners of property: the men with a stake in the country. Science, education, liberal theology, from being fashionable, had now become dangerous thoughts. The immediate transition can be seen by comparing

Godwin's (1756–1836) optimism with Malthus' (1766–1834) grim and hopeless picture of human existence (p. 729).

One fundamental advance in ideas was a direct consequence of the great changes of the time. It was the recognition of the historical and irreversible element in human affairs. According to the official, Newtonian, liberal view, Natural Laws, which had been extended from the solar system to cover the world of life and society, were deemed to hold timeless sway. All that was necessary was to discover what those laws were and to arrange industry, agriculture, and society once and for all in accordance with them. The failure of the French Revolution to institute the *age of reason* gave a chance for the alternative view of evolutionary development to gain ground. Vico (1688–1744) had indeed glimpsed this idea in regard to human societies in the early eighteenth century (p. 727), and later Buffon (1707–88) and Erasmus Darwin (1731–1802) had speculated that organisms and even the earth itself had had an evolutionary history. It was, however, left to Hegel (1770–1831) to erect these ideas into a philosophic system and for Charles Darwin (1809–82) and Karl Marx (1818–83) later in the nineteenth century to bring out the consequences of evolutionary struggles in Nature and society (pp. 734 ff.).

8.5—*THE MID-NINETEENTH CENTURY (1830–70)*

If in the eighteenth century the curious and far-sighted became aware of the arrival of mechanical industry, by the mid-nineteenth century its effects could not fail to be noticed by the most unobservant in every part of the world. Simply by increasing the scale and range of the earlier inventions a complete transformation had been worked in the lives of the tens of millions living in the newly industrialized countries. Vast new cities had shot up filled with rapidly multiplying populations. Beside the growth of industry radically new means of transport had been developed: the railways, which linked up the centres of industry, and the steamships, which collected its raw materials and distributed its products far and wide. Indeed, where the eighteenth century had found the key to *production*, the nineteenth was to find that of *communication*. No comparable change had ever occurred in human conditions

with such thoroughness and rapidity. Wherever industrialism spread the old feudal social relations were destroyed. The mass of the population became wage labourers. All economic and political initiative belonged to the new class of capitalist *entrepreneurs*. Even in the State, the relics of feudal reaction had been easily swept away in the success of the revolution of 1830 in France and of the Reform Bill of 1832 in Britain.[5.95] It had become in Marx's phrase " the executive committee of the ruling class." It was no longer so necessary to protect privilege by legislation; once property was secure, the workings of the economic system would see to it that everyone got just what he was worth.

Wealth had never been accumulated so easily; misery had never been so widespread and unmitigated by social defences. With all the new triumphs of engineering went a smoky dirtiness, drabness, and ugliness which no previous civilization could have produced. It was in this environment that science approached its present scale of activity and importance. Indeed, as we have seen, already before the beginning of the century it was an indispensable adjunct to the conduct of the new industries, and as the century progressed its range of service continually increased. It grew vastly, and as it did so it necessarily came to be directly influenced by the dominant social forces of capitalism.

It was recognized by the 1830s that a transfer of power from rank to wealth had occurred, even that it might have been necessary. True, in the French Revolution it had exceeded its due bounds, and now that an ideal state of constitutional democracy had been reached there was every reason to resist further fundamental change or even any radical criticism of the abuses of society. In the past science had been a major stimulant to such criticism. Now it was felt by scientists and non-scientists alike that as science was well established its critical and infidel role might well be laid aside.

The utilitarians

All that was necessary was once more, as in the middle of the seventeenth century, to separate the concepts of science from its social implications; to create an idea of " pure science " and so, by making science respectable again, to enable it to flourish and, even better, to become really profitable. This transformation was largely effected by the Utilitarians,

emasculated followers of the *philosophes* of the eighteenth century. Following the lead of Adam Smith and Jeremy Bentham, they deliberately set themselves the task of removing the old traditional evils of society by legislation which would leave the capitalist absolutely free. It was only thus, under the iron rules of economics as expounded by Ricardo (1772–1823) and J. Stuart Mill (1806–73), that the "greatest happiness of the greatest number" (p. 376) could be secured. In that age they were superbly confident that the eternal laws of society, as a set of freely contracting independent individuals, had at last been laid bare by science. Firmly believing their new prophets, the entrepreneurs of the golden age of capital set themselves out to prove how right they were. In the enormous burst of productive activity that went on, without any but minor set-backs, from 1830 to 1870 science was to have a small but vital and growing share.

This was the period of the heyday of capitalism, with its extravagant wealth and grinding poverty; the period of the Chartists and the Hungry Forties as well as that of the Exhibition of 1851. Capitalism had indeed already, as Marx predicted in 1848, brought into existence the dispossessed working class whose eventual power was to bring capitalism's rule to an end. But that day was still far off, and although the fight for better conditions never ceased, increased production and expanding markets did for long enable the capitalists to make timely concessions to the standard of living of the working class.

The mid-nineteenth century was not a period of radical technical transformation that can compare with the eighteenth. It was rather one of steadily improving manufacturing methods operating on an ever larger scale. Though rivals were beginning to enter the field, the advantages Britain had won in the Industrial Revolution were retained and even improved on. For a while Britain was literally the workshop of the world. The cheapness of the goods, predominantly the textiles produced by the new machinery, extended the markets in a way that seemed for decades unlimited. That market could be met by simply multiplying and steadily improving existing types of machinery. There was therefore no violent urge for new devices in production. There was, on the other hand, an ever-increasing need to speed up *communication* and *transport*. The *telegraph* was the first practical and large-scale application of the new science of electricity. Materially more important

was the application of power to transport in the *railway* and *steamboat*; here science was only in an ancillary role.

The rise of the engineers

Both were directly the product of the new profession of mechanical engineers and were made possible by the availability of cheap iron, now smelted with coal, on a scale many times that of any previous age. The appearance of the modern engineer was a new social phenomenon. He is not the lineal descendant of the old military engineer but rather of the millwright and the metal-worker of the days of craftsmanship. Bramah (1748–1814), Maudslay (1771–1831), Muir (1806–88), Whitworth (1803–87) and the great George Stephenson (1781–1848) were all men of this type.[5.78–80] The growth of the applications of science in the mid-nineteenth century was so much more rapid than the growth of science itself that their handling and development fell into the hands of practical men. These, for the most part—only the greatest like Richard Trevithick (1771–1833), George Stephenson, and I. K. Brunel (1806–59) were exceptions—proceeded to deal with them as their predecessors had, by trial and error, and to superimpose an evolutionary technical development on the revolutionary innovations that had come directly from science. Thus the reciprocating steam-engine, in spite of nearly 200 years of improvements, is essentially the same machine that left the workshops of Boulton and Watt in 1785.

The railways and the steamboat

The railways were originally the products of coal-mining. The great innovation of putting an engine on wheels to make it a *locomotive* also was most successfully attempted in the mines (p. 418). The railway age covered Britain with its network in the 'thirties and 'forties and spread to the rest of the world throughout the century. It also led to an enormous increase in the older, civil engineering which carried on the tradition of the eighteenth-century builders of canals, roads, and bridges, like Macadam and Rennie. It can still be seen in the great works of Robert Stephenson and I. K. Brunel. A new interest in geology came from the making of canals and railways, which revealed the structure of the rocks in cuttings and tunnels while at the same time it provided, in the profession of surveyor, a new source of income to the geographical and geological sciences.

The telegraph

The improvements in transport brought about by the railway and the steamship put a premium on rapid communications. The need to transmit news rapidly is as old as mankind, as many beacon hills bear witness; but short of magic or telepathy there was little means of realizing it except for alarm calls. Even the needs of war had not produced anything more elaborate than the relay semaphore telegraph. And yet the means had lain to hand for some time. Already in 1737 electricity had been used to transmit messages for distances of several miles, but the use of static electricity was difficult and unreliable. It was the coincidence of the advent of railways with Oersted's discovery of the effects of electric currents on a compass that provided a cheap and foolproof method just when the need was greatest, and ensured the successful invention of the electromagnetic telegraph.

The actual impetus that set a host of inventors working at the same time (e.g. Morse, Wheatstone, etc.) was not any general need of social communication but the actual money value of news of the prices of goods or stocks and of events that might affect them. News meant money, and the electric telegraph provided the means to convey news rapidly.

Short-distance telegraphy was a very direct application of electricity, requiring only a very elementary alphabetic code; but the need for its extension to greater distances and greater speed was to tax the ingenuity of physicists up to the present day and to give rise to much fundamental knowledge and delicate instrumentation. In particular the working of the Atlantic cable, linking Wall Street to the City, was only ensured in 1866 owing to the ingenuity of one of the greatest physicists of his day, William Thomson, Lord Kelvin (1824–1907). Even more important for the general position of science was the fact that the telegraph created the need for trained electricians, and this in turn for technical schools and university departments of physics, on which most of the advances of the later nineteenth century depended (p. 442).

By the 'fifties science was already paying dividends. A new chemical industry was rising, based mainly on the need of the expanding textile industry for soda and sulphuric acid; and the discovery of aniline dyes secured the future of organic chemistry. A beginning was being made to enlist science, particularly chemistry, in the improvement of agriculture through the use

of artificial fertilizers (p. 477).[5.4] Biology was also beginning to find new uses outside the traditional field of agriculture. The chemist, Pasteur (1822–95), was finding means of improving the manufacture of beer and wine and was making his first successful attack on a disease, not of man but, characteristically, of the economically valuable silkworm (p. 472).

Here, for the first time, was the possibility of a scientific, as distinct from a traditional, control of living processes. Even medicine was beginning to move with the times and to accept rather grudgingly such gifts as anæsthetics from the new chemistry. Actually, thanks to poverty, overcrowding, and *laisser-faire* economics generally, the health of the people in industrial countries was probably worse than at any other period in their histories. Disastrous epidemics of oriental cholera, brought in through the new facility of transport, continued to occur until their very virulence, and the threat they offered to the middle classes themselves, led to an understanding of the need for sanitation and put some check on the practices of slum landlords (p. 474).[5.77a]

The organization of science

The facilities for either the practice or the teaching of science by no means corresponded to the function science was already filling in economic life. This was particularly true of England, where science was finding the greatest field of application.[5.7] By 1830 a group of young British scientists under the leadership of Charles Babbage (1792–1871) were especially vocal about the failure of both the Government and the Royal Society, its agent in science, to react to new needs. In his book *Reflections on the Decline of Science in England*,[5.14] Babbage pointed out that the Society had become effectively a closed corporation of officers, controlling a membership the majority of whom had only a nodding acquaintance with science and who were not even its generous patrons. Reform was in the air, but the Royal Society took its time, and by the simple device of restricting its new membership only succeeded in reaching, some years after his death, the state that Babbage demanded.[4.6]

The British Association

Babbage was, reasonably, impatient and managed, with his friends, to found in 1831 *The British Association for the Advancement of Science*; a substitute which could be counted on to act

and speak on behalf of science. This was modelled on the *Deutscher Naturforscher Versammlung*, founded in 1822 in Germany by Lorenz Oken (1779–1851), one of the most ardent and fantastic of "natur Philosophen" (p. 469) but a staunch liberal who gave up his chair at Jena in 1819 rather than to submit to censorship of his magazine *Isis*. The movement he had started, was, in fact, to be the herald of the great scientific renaissance of Germany in the mid-nineteenth century.[5.85] The British Association was, in its way, as successful. It rapidly became an institution which, though never as august, was far better known than the Royal Society from its habit of carrying its meetings to every city in the United Kingdom and even to the colonies. These meetings were the battleground of all the great scientific controversies of the time, notably those of the conflict of science and religion, culminating in such events as Huxley's retort to Bishop Wilberforce at Oxford in 1860 and Tyndall's Belfast address of 1874 suggesting that life might have come from inanimate matter. It was in part a society for popularizing science, and in part one for promoting and financing research in the interest of the nation. It undertook, for instance, to further the study of seismology, tides, meteorology, magnetism, electrical standards, geology, and biology. Effectively it did by private enterprise what elsewhere was the concern of government. By the end of the century the burden became too great, and was at last shifted by the creation of such institutes as the National Physical Laboratory. One of the Association's actions that was to have the largest consequence was the request it made to Justus von Liebig (1803–73) to prepare a report on agricultural chemistry, a task which turned that great chemist's attention to the practical problems of food production and which was the starting point of the sciences of soil chemistry and nutrition (pp. 459, 477).

Such activities represented the need of the new industrial bourgeoisie to take science into its own hands and to break into the exclusive upper-class and university circles to which it had returned in the early decades of the century. By the mid-century they had been largely successful and the new importance of science had obtained institutional recognition.

The scientific societies

The general societies, which had sufficed the seventeenth and eighteenth centuries, could not cope with the flood of specialized

knowledge that was creating new fields of science. In France, England, Scotland, Germany, and elsewhere, chemical, geological, astronomical, and other societies were founded, each with its appropriate journal, while at the same time engineers began to associate themselves into institutes.

Science in the universities

It was also in the mid-nineteenth century that the opposition of the English and French universities to the new science, maintained for over 200 years, began to break down. In England this took place partly by the setting-up of new colleges, later to become universities, in London and in manufacturing towns, and partly by adding new departments to already existing universities.[5.90a] While at the beginning of the century many, if not most, great scientists in England were amateurs or had been brought up as apprentices, as were Davy and Faraday, by the middle of the century the university professor, already well known on the Continent, began to be the type of the scientist in England.[5.42a] The Great Exhibition of 1851 was a symbol of the unity of science, invention, and manufacture, and some of the proceeds went to founding a scientific teaching centre, the Royal College of Science, in South Kensington. In France the decisive step had been taken much earlier with the establishment of the École Polytechnique and the École Normale Supérieure (p. 380).

It was pre-eminently Germany that took the lead in assimilating science into regular university life. The German universities had indeed begun their reform in the period of the Enlightenment in the eighteenth century. The lead was taken by Göttingen, founded in 1736 by George II in his Hanoverian dominions. From the eighteen thirties onwards the universities of the diverse German States vied with each other in the foundation of scientific chairs and, though more slowly, of teaching laboratories, of which Liebig's at Giessen was the prototype. Germany had come late into the scientific movement; it had a more disciplined and less independent official class than France or Britain. It was able, however, to supply by organization what it lacked in individual initiative. By the middle of the century, and increasingly thereafter, Germany turned out trained scientists, text-books, and apparatus to supply needs far beyond its boundaries.

All these changes resulted in a vast increase in the volume and

prestige of scientific work. It acquired a more and more formal organization, and its pursuit became a profession comparable to the older professions of law and medicine. In doing so, however, it lost much of its early independence, its amateur status. Science did not so much transform the universities as the universities transformed science. The scientist became less of an iconoclast and visionary and more of a pundit, the transmitter of a great tradition. Particularly in Germany, where scientists had first been associated with the liberal movement, they became, after the fiasco of 1848, among the staunchest supporters of the official State machine.[5.3]

Middle-class and popular science

Science was to remain for many years the monopoly of a select part of the middle classes—the liberal intelligentsia as they were known in Europe—and inevitably continued to be limited and coloured by their world outlook. In the middle of the nineteenth century they did not scorn utility. They were interested in the great industrial movements of their time. They believed firmly in the inevitability of Progress, but they repudiated all responsibility for any of its unpleasant and dangerous results. Nevertheless, though advancing in wealth and authority, their relative political and economic status had fallen. Industry and finance had advanced in power far more rapidly than science. While in the eighteenth century the leading scientists were on dining and marrying terms with the captains of industry, relatively few could—or seriously wanted to—reach the seats of wealth and power in the nineteenth.

Indeed, for all its growth and extension in the nineteenth century, science only managed to penetrate fitfully, either up or down, beyond the circle of the middle classes. Count Rumford's efforts at the turn of the century to found an institute for the training of mechanics had resulted, after a few years, in a Royal Institution for the scientific entertainment of the nobility and gentry, and only incidentally in the creation of a brilliant research laboratory as well. Other mechanics' institutes succeeded better in their original objective, notably one founded in the City of London in 1823, from which Birkbeck College was to emerge (pp. 733, 811). These, however, and the improving lectures given by eminent scientists like Thomas Henry Huxley to the lower orders touched only an insignificant fraction of the new working class which the

Industrial Revolution had called into existence. As to technical education, it hardly existed in Britain, the home of mechanical industry, until the twentieth century.[5.3] Those who did not, or could not, resort to "self help" as a way of getting into the middle classes were apt to regard science and technical innovation generally as a means of cutting wages and producing unemployment (p. 298).

The vision that the new powers of science would make it possible for the working class to get rid of the oppressive system of capitalism, foreshadowed in the pioneer experiments of Robert Owen, was first clearly enunciated by Marx in the *Communist Manifesto* and later elaborated in *Capital*; but the full impact of this doctrine was not to be felt till the next century (pp. 824 f.).

8.6—*THE NINETEENTH-CENTURY ADVANCES OF SCIENCE*

The mid-nineteenth century registered progress in science over such a wide front that it is impossible in a few pages to do more than pick its major achievements. Physics, chemistry, and biology all expanded and proliferated into separate sub-sciences. There was a great search over all the fields of Nature and technique, such as Bacon had dreamed of but not carried out, by minds already trained in the disciplines of observation, experiment, and calculation bequeathed by the seventeenth and eighteenth centuries. All the previously developed fields continued to deepen their analysis and to find new outlets in practice.

The triumph of chemistry

Chemistry was especially *the* science of the nineteenth century. This was essentially because it was the major science ancillary to textiles, which all through the century was the most important industry. As will be told in its place (pp. 444 f.), chemistry grew on the secure basis of the revolutionary establishment of the atomic theory and rapidly came to be able to deal with all types of substances. What is important here is that as the century passed, chemistry came to colour in a literal, as well as a figurative sense all products of manufacture. New cheap synthetic materials—adulterants, perfumes, dyes, largely drawn from coal tar—came to replace those natural products too dear

and rare to cover the new markets. It was in this transition that the centre of chemical research moved from its birthplace in Britain in the eighteenth century, through France, where it was codified and enlarged, to Germany, which was the first country where its multifarious uses were realized in practice. This transition was to prove of sinister consequence in the next century.

The conservation of energy

Amid this active advance of science, old and new, two great generalizations stand out as the major contributions of the nineteenth century. One, in the field of physics, was the doctrine of the *conservation of energy*; the other, in the field of biology, was that of *evolution*. The former, as we shall see (p. 421), represents the realization, by a whole host of scientists from Carnot to Helmholtz, of the importance, as a cosmic principle, of the interchangeability of different forms of energy. Effectively, it was inspired by the study of the conversion of coal to power that had already been achieved in practice by the steam-engine from the dawn of the Industrial Revolution. It was given a more and more mathematical form and emerged as the science of *thermodynamics*, the first law of which, the conservation of energy, is coupled with a second law which determines its limited availability. It is characteristic of the time that the second law should have been discovered by Sadi Carnot as early as 1824, for it is this law, and not the first, that limits the amount of work that can be got from each ton of coal by an engine of given design. This *efficiency* of engines at that time rarely rose to as much as five per cent.[5.3]

The first law of thermodynamics provided a principle of unification by showing that the forces of Nature previously considered separate—material movement, sound, heat, light, electricity, and magnetism—were all measurable in the same units, those of *energy*, the quantity of which in the universe neither increased nor decreased. Its formulation recalls over the centuries the dictum of Heraclitus (p. 121) on change "as gold for goods and goods for gold" and is indeed the physical expression of the principle of free trade, established in practice at that very time. The conservation of energy was a magnificent extension of Newton's principle of conservation of motion but, like it, contained in itself no conception of progressive change. Change did indeed follow from the second law, but in

the form of degeneration rather than progress, for it showed how in any closed system the heat and the cold must ultimately come together in a uniform tepidity from which no more energy could be extracted (p. 423).

Evolution

Such a conception accorded ill with the progressive and optimistic mode of the nineteenth-century bourgeoisie, who found a congenial scientific justification in the theory of *evolution.* The idea that the earth had a long history was not new. Indeed, as we shall see (pp. 465 f.), it began to take form in the eighteenth century and its acceptance was held back only in the reaction of the early nineteenth century by clerical prejudice. With it came the realization that animals and plants were once very different from what they are now, and the obvious implication that the latter might be descended from the earlier forms. The evidence, however, that was accumulating all through the nineteenth century, derived from the experiences of the age of canal and railway building, made any other explanation very hard to believe. At the same time greater knowledge of the distribution and classification of living animals and plants made the idea of special creation appear more and more arbitrary. Nevertheless it took years of patient and obscure work by generations of geologists and biologists before the world could be made to listen to and begin to accept the idea of organic evolution, with its stinging corollary that man was descended from animals. It needed all the insight, skill, and scientific reputation of Charles Darwin to secure a hearing even as late as 1859 for such a radically new idea with the publication of the *Origin of Species.*

From the moment it was propounded the theory of evolution became the centre of a scientific, ideological, and political battle. Darwin had, almost unwittingly, made as damaging a break in the Platonic doctrine of ideal forms in the animate world as Galileo had in the inanimate. And Darwin did more than assert evolution: he provided a mechanism—*natural selection*—that destroyed the last justification for the Aristotelian category of final causes. No wonder the theologians, whose whole world-picture was finalistic, repudiated it. Even more shocking was the idea that man himself—that unique end to creation—was nothing more than a remarkably successful ape. This seemed not only to shatter the doctrine of religion but also

the eternal values of rational philosophy. Both were to recover from the blow only too easily (p. 483).

At that time, however, evolution was at the centre of the battle between progress and reaction. For the doctrine found supporters as well as enemies. It was a weapon in the hands of materially minded industrialists against sentimental Tories on the one hand, and idealistic Socialists on the other. It seemed to give a scientific blessing to the exercise of unfettered competition and to justify the wealth of the successful by the doctrine of the *survival of the fittest.* As Darwin's views continued to gain ground and won the enthusiastic support of a new generation of scientists, science itself began to take on again a radical tone, but as yet it was far from a socialistic one.

The prevailing school of thought following John Stuart Mill, Auguste Comte (1798–1857), and Herbert Spencer (1860–1903) tended to justify, in terms of logic and science, the freedom of private enterprise and to praise the nineteenth century as the era in which man had at last found the right way (p. 746). It was not perfect yet; there were still some abuses of the past to be swept away; and progress would continue; but that progress was envisaged as a direct extension of the present—more machinery, more inventions, more accumulation of wealth, even more comforts honestly earned by the deserving poor following the gospel of "Self Help." Samuel Smiles (1812–1904) who coined that phrase in his series of biographies of the makers of modern industry showed a sense of significant history far ahead of his contemporaries. Although associated with the doctrine of rugged individualism, he had, towards the end of his life, realized that something more was needed than "self-help," and became a pioneer of technical education for the workers.[5.80]

The rise of Socialism

What the poor thought about the benefits of progress was shown in the Chartist and other revolutionary movements of the mid-century and, at the end of the phase, by the insurrectionary Commune of Paris of 1871 following the miseries of war and siege. Their philosopher, Karl Marx, of whom more in his place (pp. 734 f.), was barred out of the consciousness of the comfortable intellectual classes. Nevertheless, the more honest of these could not help using their eyes and their noses to realize that there was something desperately wrong at the very heart

of nineteenth-century prosperity. Artists, poets, and writers were moved to protest against the horrors of the new industrial towns, against the universal degradation of beauty, against the vulgar flaunting of wealth. In opposing them these intellectuals found their first support in an attempt to return to an idealized "Middle Ages." Keble (1792–1866) and the Oxford movement, Ruskin (1819–1900) and the pre-Raphaelites, marked the first reactions which, towards the end of the century, were to become part of the full-blooded Socialism of William Morris (p. 758).

Science and culture

Rejecting industrialism, the literary and artistic movement also largely rejected science, which they felt, with some justification, had identified itself with machine production and all that it had brought in its train.[5.24] It was from this period in mid-century that the split between the humanists and scientists, which is such a feature of our own times, first became serious. Its immediate effect was to prevent the co-operation between the two branches of intellectuals without which no constructive criticism of the economic and social system was possible. The humanists never knew enough of how it worked to have other than ineffective emotions about it; the scientists were blunted by a quite deliberate turning away from everything—art, beauty, or social justice—that did not come within the purview of their, by then, highly specialized work.[1.2.146]

8.7—*THE LATE NINETEENTH CENTURY (1870–95)*

Already towards the end of the 'sixties the first, simple, optimistic phase of early capitalism was beginning to draw to an end. The great depression which started in the 'seventies marked a transition between the era of free-trade capitalism, with Britain as the workshop of the world, and that of a new, more widely based, finance capitalism, with France, Germany, and the United States coming to the fore under the cover of protected markets. The enormous productive forces liberated by the Industrial Revolution were by then beginning to present their owners with the problem of an ever larger disposable surplus. This could not, under capitalism, be returned to the

workers who made it. When invested at home it led to even greater production and to a more hectic search all over the world for markets that were soon filled. The result was colonial expansion, minor wars, and preparations for the larger wars which were to come in the next century.

As a transitional phase it is a difficult period to demarcate, particularly in science. It is certainly easier to do so in retrospect than at the time, for the change here was a gradual one without any marked break in continuity. To those living through that period it seemed that science was moving faster and faster. Nevertheless, doubts had begun to appear as to whether its use was leading to a future of unlimited and beneficial progress. Looking back we see the later nineteenth century as a period which was at the same time an ending and a beginning, a quiet winding up of the great scientific drive of the Newtonian period and a preparation for the stormier scientific and political revolutions of the twentieth century.

In industry, too, the period was transitional. While the old industries continued to expand more slowly in Britain and very rapidly in Germany and the United States, a change was coming over their character. Competition between small family firms led to the formation of big joint-stock companies, soon to become the giant monopolies of the twentieth century. This transition was particularly marked in the metal and engineering industries, in which science was being brought in again after a long run of practical men, and even more in the new chemical and electrical industries which owed their origins entirely to science. With their growth there appear for the first time the Kelvins, the Edisons, the Siemens, the Brunners; not business men turned scientists, but scientists turned business men.[5.3]

We also see, for the first time, a large-scale application of science to war: the submarine, the torpedo, high explosives and big guns, the beginning of the mechanization of warfare. The major industrial characteristics of the end of the nineteenth century were the advent of cheap steel and the introduction of electric power. It also marked the beginning of the use of the internal-combustion engine, which was to revolutionize the transport of the next century. Not less important in their ultimate consequences were the first successes of scientific medicine in reducing the toll of infectious diseases and permitting the exploitation of tropical areas.

The age of steel

The first step in the use of science to transform the traditional iron industry came with Bessemer (1813–98), himself a scientifically minded manufacturer quite outside the industry. His converter, introduced as early as 1854, showed that steel could be made cheaply on a large scale; but the converter was still of only limited use because it required high-grade ore. It was not till 1879, when Gilchrist Thomas introduced the basic-lined open-hearth furnace, that low-grade ores could be used for steel-making and production leaped upwards (p. 430).[5.87]

What is more significant for history was that this changed the geographical centre of gravity of heavy industry. With the basic open-hearth the great phosphatic ore deposits of Lorraine became available for steel-making. In 1870 these had been united with the coal of the Ruhr through the success of the freshly industrialized Prussian State in its war against France.

The rise of German industry

From now on there would be in Europe a centre of steel production which was soon to equal and surpass that of Britain, and on this steel was based a new industry better organized and more closely linked with the State than hers. Britain, however, with her multifarious and competitive industries, still kept a leading, though diminished, place in world markets, particularly by reason of the hold she possessed over all the undeveloped parts of the world.

Rivalries were inevitable and were to be the prime cause of the wars of the next century. In the first stages they expressed themselves, largely owing to the availability of cheap steel, in such exports of capital as rails, locomotives, and agricultural and mining machinery for opening up new territories. These supplemented the still expanding sales of cloth, trinkets, small arms, and hardware, on which the mid-nineteenth-century colonialism had been based. What was left of the steel and particularly of the newly developed alloy steels went into battleships and big guns (pp. 493 ff.).

The electrical industry

Electricity, as we have seen, played a vital part in the revolution in communications of the mid-nineteenth century. The generation of electricity by mechanical force and its use for power transmission were quite evidently feasible (p. 440) after

Faraday's discovery of electromagnetic induction and his demonstration of the electric dyna-motor in 1831. The reasons it was not used for fifty years were, as will be shown, not mainly technical but economic.[5.3] Mid-nineteenth-century industry ran on relatively large concentrated units of power—stationary steam engines for factories, the locomotive or marine engine for traction. The only way of transmitting energy over large distances was by the shipping of coal. Later, the increasing mechanization of minor industries was to call for smaller power units than steam could conveniently supply. The solution was first found in the gas-engine, the first practical internal-combustion engine and the forerunner of the oil and petrol engines that were to revolutionize transport in the twentieth century.

The electric motor was to prove a far more flexible means of satisfying the industrial need of small static power units. Its whole value, however, depended on the availability of a widespread network of electric power supply, and this could only be brought into existence by a more general need than that of industrial demand. This need was to come from the evolution of domestic services. As the century progressed, extended networks of water and gas supplies, and later of telegraphs and telephones, were laid down. It was an enterprising telegraph clerk, Thomas Alva Edison (1847–1931), who jumped ahead of other competitors and led the way for another such extension—the electric light (p. 442).

Once electricity had to be *made* and *distributed* for light, it could be *used* for power, and a new universal and cheap means of distributing energy was made available to industry and transport, though this was not to be fully effective until the twentieth century. These developments created the heavy electrical industry, which, in contrast to older industries, was monopolistic and scientific from the outset. It was closely linked with other growing monopolies in heavy engineering and with telegraph and telephone monopolies. For science it had another capital importance: it created the industrial research laboratory. Edison's Menlo Park, originally just a barn for trying out inventions, showed the necessity for continuous experiment closely related to production.[5.72]

Scientific medicine

While these advances were transforming the manipulable material environment of man, one of even greater importance

was taking form: the beginning of a scientific medicine. The reason that this did not take place until such a late date was because the constitution of living organisms was so many times more complicated than that of the most complex mechanical or chemical system that these had first to be understood before a successful attack could even be launched.

Medicine had existed as a mystery and a profession from the very dawn of civilization, but, despite all the progress in the knowledge of anatomy and physiology in ancient and modern times, the doctor could do little more than alleviate the pains and anxiety of the patient and forecast more or less accurately the course of the disease. As human beings recover naturally from most diseases the doctor's care was usually rewarded. The formidable array of drugs in the pharmacopœia had been compiled partly from the simples of ancient medicine, based on a mixture of folk medicine and magic, and partly from the more violent metallic drugs introduced by Paracelsus in the Renaissance (p. 272). Almost all of them were useless.

Here and there, for instance, in the use of quinine for malaria and of vaccination against smallpox, a few specifics of preventive measures had been hit upon only by fortunate accidents, but for lack of adequate experiment or theory it had been impossible to generalize them. As will be told later, discoveries arising initially from the application of chemistry to the old biological industries of brewing and wine-making led to the first understanding that killing diseases such as anthrax, hydrophobia, cholera, and plague were the result of the invasion of the body by living organisms from outside; and revealed at the same time the way to combat infection by them and, even better, to prevent people from catching them (pp. 473 f.).

From now on, in principle at least, the way to the conquest of disease was open. In its earliest stages it showed that man himself could, through the use of science, overcome what had always before seemed the blind malevolence of fate or an inscrutable providence beyond his control. In this alone, science had justified itself. Yet the very advances of the new medical science now brought into ever sharper relief the conditions of industrial or colonial poverty that underlay and supported the civilization that seemed so rich and powerful on the surface. The root causes of disease were not in the germs but in the conditions that enabled them to breed and spread, and no vaccine

or serum could deal with this evil, which was endemic in the economic system itself.

The race for colonies

By the end of the century industrialized Europe, largely concentrated on the coalfields that ring the North Sea, had so multiplied in population that it was no longer directly self-supporting. Ever-increasing quantities of food and raw materials had to be imported from eastern Europe, particularly Russia, and from America. It was this demand that led to a rapid transformation in methods of agriculture and of the preservation and transport of food. The development of agricultural machinery, while it did not usually increase the yield per acre, enormously increased that per man. It was especially applicable to open country with a small population, and hence to America, rather than to the older, still feudal village cultures of eastern Europe and Asia.

The introduction of agricultural machinery and the associated rail and steamer transport radically altered the relation of man to his food supply. Before then, even after the eighteenth-century improvements, some eighty to ninety-five per cent of the food produced was consumed on the spot; the town workers and the idle rich, always a small minority, could dispose of only the remaining five to twenty per cent. Countries that lived by trade, like seventeenth-century Holland, or by manufacture, like nineteenth-century Britain, could maintain large urban populations only by drawing on the small individual agricultural surplus of millions of peasants throughout the world. Now, the land workers, using agricultural machinery, could be a dwindling minority and yet provide a hitherto unimaginable surplus for the towns. While this was true at first of grain foods, the principle of urban concentration of food could be extended to meat and fish only by the introduction of refrigeration and canning, involving much physical, chemical, and biological research and development.

These methods of mechanical exploitation, applied mostly to virgin land, had much in common with the mining ventures that were widespread in that period, but, covering a larger area, they were much more destructive in their effects. Exhaustion of the soil was only partially palliated by the use of artificial fertilizers, and the way was open to the devastating erosion of the next century.

In the opening up of Western and Eastern lands, first to agricultural, then to industrial exploitation, which was largely made possible through the use of steel for agricultural machinery and transport, the financial capital of the older countries found its most profitable outlet. The fate of these investments in these two areas was to be very different. North America, from its foundation a colony of the bourgeoisie, was, even before the Civil War, producing its native capitalists, who were growing rich on the previously untapped resources of the continent and on the labour of tens of millions of poor emigrants from Europe. The Duponts, Astors, Rockefellers, and Morgans were soon to surpass their European forerunners in wealth and power and to turn the United States into the citadel of capitalism.

In Russia, on the other hand, autocracy and the relics of feudalism, combined with an intense exploitation by British, French, and German capitalists, held back development for a time, but when they were swept away in the Revolution the way was open for the first Socialist State.

In the East, India remained for direct, and China for indirect exploitation; but one State—Japan—was allowed to become a model of the civilizing value of a native capitalism, creating all the appearances of the new "Western" culture, including science, but using them to build up on a feudal basis an uninhibited, predatory, and militarized State.

8.8—*SCIENCE IN THE LATE NINETEENTH CENTURY*

In a period so short and so crowded with practical achievement as the late nineteenth century it is not to be expected that many great theoretical advances would be made. In the physical sciences the period was pre-eminently one of transition, with the rounding off of the great advances of the early nineteenth century, and at the same time with the beginnings of investigations of a new kind that were to lead to the explosive advance of the twentieth century. In biology, on the other hand, new ground was being broken in the study of microbes and in the approach to a physical–chemical understanding of physiology.

The electromagnetic theory of light

The major achievement of the period in physics was the formulation by Maxwell of the *electromagnetic theory of light.*

This brought together in one comprehensive theory the results of two generations of experiments and theories in different fields of physics—electricity, magnetism, and optics—and gave them a simple mathematical formulation. Though in itself a triumph of mathematical physics, it depended for its verification on the establishment of accurate units for electricity, a task made necessary by the rise of the electrical industry. In turn, Maxwell's equations were to form the theoretical basis of future electrical engineering, an intricate interplay of theory and practice.

The electromagnetic theory was a crowning achievement which realized the dream of Faraday that all the forces of Nature should be shown to be related, and, together with the laws of thermodynamics, seemed to imply a certain finality in physics—an idea that was to be rudely shattered in the twentieth century. It was, however, also to be a beginning, for its central concept—the theoretical necessity for the existence of electromagnetic waves—was to lead to their experimental demonstration by Hertz in 1888, and from this to their practical utilization in wireless telegraphy and all that was to result from it.

The periodic table of elements

In chemistry the period included one major generalization, the *periodic table* of Mendeleev (p. 523), put forward in 1869, which also appeared at the time to set a limit to the existence of fundamentally different kinds of matter, but which was actually to find its full interpretation in a new concept of matter no longer made of immutable atoms but by relatively impermanent associations of a few fundamental particles themselves liable to change and transformation. Mendeleev was the Copernicus of the atomic system; its Galileo and Newton were still to come.

In organic chemistry, once the confusions due to a reluctance to accept the atomic theory had been overcome, there was a magnificent and ordered advance in the interpretation of the structures of natural substances and an even more impressive deliberate synthesis of new ones. By the end of the century chemical research was fully embedded as an essential part of the new chemical industry, which was now reaching out from its triumphs in synthetic dyes to those of synthetic drugs (p. 460). The chemists had so multiplied in numbers as to represent well over half of all workers in science.

Research laboratories

This greater utilization of science and scientists called for large extensions in scientific education and in the organization of science. The only organizational innovation was the advent of the industrial research laboratory, which grew up almost imperceptibly from the workshop or private testing place of the inventor turned business man, such as Siemens or Edison. But university laboratories also grew, from the very fact that the new uses of science meant new jobs and attracted more and more students. Thus, despite all the protestations of disinterestedness, the academic science of the period was ultimately dependent on the success of science in industry. Nevertheless it was left for the most part to the enjoyment of considerable liberty as long as it respected conventional limits in politics and religion.

The dominance of German science

The largest increase was to be found in Germany, which, from the number of its universities, its newly founded *Technische Hochschulen*, and its innumerable *Zeitschriften* and *Handbücher*, tended increasingly to dominate the scientific world towards the end of the century. Britain and France, relying on their own great traditions, resisted this tendency, but the German language became pre-eminently the international language of science, and German professors set up a kind of scientific empire which covered all northern, central, and eastern Europe and exerted considerable influence on the science of Russia, the United States, and Japan. The German professor was on the way to becoming the model for the scientists of all the world. Like most of the German intellectuals, he had made his peace with the alliance of military feudalism and big business which ruled that newly industrialized and expanding State. That allegiance was to point to the next stage in the development of science, in which it was to come to be used in the service of the State predominantly for military ends.

The great depression

The end of the nineteenth century, like its beginning, was marked by a philosophical reaction tending to limit severely the field and significance of science. But whereas the early reaction was directed in opposition to the effects of the French Revolution, the later one was dictated by an anxious awareness

of a social revolution to come. In spite of the enormous new wealth that was being produced by industries ever more scientific in their operation, in spite of the prospects of further advance, the strains of society seemed to increase rather than diminish, and there could be no denying a sense of frustration and doom in the ranks of the cultured intellectuals, a *fin de siècle* feeling that was to be only too well justified. Especially in Europe, Marxist Socialism seemed to be providing a hopeful alternative for the industrial working class. It was there, accordingly, that the current of philosophy was most directly affected, but Britain and America, for all their traditional indifference to philosophy, were not immune.

There was a turning back from the implicit and optimistic materialism of the mid-century towards the neo-positivism of Mach (1838–1916) and Ostwald (1853–1932), who, under the guise of purging science of unnecessary mental constructs, removed matter and replaced it by bundles of sensations or convenient fictions. This philosophy and others like it, such as the *élan vital* of Bergson (1859–1941) and the pragmatism of William James (1842–1910), all tended to take the revolutionary sting out of science, to laugh out of court any idea that it could be used to effect any significant improvement in the lot of man, and to make it acceptable to organized religion and the State (pp. 753 f.).

These philosophies were indeed only symptoms of the absorption of science, as a consequence of its growing technical indispensability, into the machinery of capitalism. The change in the scientists' attitude towards pure science and away from social responsibility was made easier by increased endowments, permitting greater specialization, and by a discreet distribution of honours and patronage. The very increase in the number of scientists also reinforced this tendency to conform and escape responsibility. By the end of the century, the independent scientists were a small minority. The majority drew their salaries from universities or from the Government, and more than ever assimilated the mentality of the ruling class.

How far these conformist tendencies held back the development of science will always be hard to tell, because in actual history their influence was outweighed by the enormous expansion in the scale of science itself. But that there was some such retarding effect seems to emerge from all detailed studies of the advance of particular sciences.[5.3] It is not so much that

phenomena have been missed or that, when observed, conclusions that afterwards seem to be obvious have not been drawn from them, though this has certainly occurred over and over again; it is rather that in the social system of the late nineteenth century there existed no real sense of direction or idea of the relative significance of different fields of work. Had there been such, many of the great discoveries which were to come at the turn of the century could have been anticipated by twenty years or more. The effort wasted on fruitless refining of old theories would have amply sufficed to have brought the new to light. It may be said that such an idea was alien to science at the time—some say it is so still—but there can be no doubt that the all-round, organized scientific drive of great periods, such as those of the mid-seventeenth and late eighteenth centuries, and even of the mid-nineteenth century, seemed to have vanished. It was not until the disturbed period of the twentieth century that it was to appear again in full vigour.

This closes the account of the general development of science in the eighteenth and nineteenth centuries. A general appreciation of the achievements of that great era is deferred to the end of Chapter 9, after considering in more detail the progress of the separate sciences.

Chapter 9

DEVELOPMENTS OF THE SCIENCES IN THE EIGHTEENTH AND NINETEENTH CENTURIES

9.0—*INTRODUCTION*

By the time the eighteenth century is reached the relations of science with society can no longer be set out as one simple time sequence. It was necessary to begin with such a sequence because without it the histories of the sciences remain mere chronicles; but by itself it conceals the inner connections of particular sciences that run on continuously over the whole period. In each science the parallel growth of understanding and control depends both on inner and outer factors. The inner determinants are the hard facts of Nature: the structure of matter and the events and characters of its evolution. The outer determinants are the technical, social, and economic capacities and drives that link with general history. These, though they may not determine what is found out, are decisive in determining when and how new facts are brought into the cumulative tradition of science. To understand fully how this happens it would be necessary to follow the history of science in detail, with wider knowledge and critical ability than have usually been brought to bear on it hitherto. I can make no claim to do so here, but will try merely to exemplify some of the principles of the interaction by a treatment in outline of some selected fields of science and technology that between them bring out the general character of the advances of the eighteenth and nineteenth centuries.

The fields I have chosen are those of Heat and Energy (9.1); Engineering and Metallurgy (9.2); Electricity and Magnetism (9.3); Chemistry (9.4); and Biology (9.5). In the last part of this chapter (9.6) I have attempted to pull together the material in this and the preceding chapter and to examine the lessons to be drawn from the time and subject sequences. The choice of subjects has been made to bring out the major features of the eighteenth–nineteenth-century transition from a science

which was largely academic to one beginning to play an essential part in economic life. In all but the second case, each subject includes one or more economically important development linked with the discovery of some principle of fundamental scientific importance. Thus the first section contains the history of the steam-engine, and shows how attempts to increase its efficiency led to the discovery of the laws of *conservation* and *transformation* of *energy*. The second section is, in a sense, an appendage of the first, for it was the exacting demands of the construction of steam-engines and steam-driven machinery that led to both the precision methods of metal-working and the production of improved metal in quantity, leading to the *age of steel*. Here no great scientific principles are involved and the amount of science called on is relatively small. The value of the study of engineering is that it brings out first how much of the mechanical transformation depended on simple workmen and secondly how essential precision metal-working was, both to industry and science. In the story of steel the emphasis is rather on the enormous technical and economic advances that were achieved by the employment of relatively little scientific knowledge.

In the third section, on electricity, we have a different case again—the study of the transformation of a subject of purely scientific and even frivolous interest into a major industry. At the same time it should serve to bring out how the applications of the mathematical mechanics evolved in the seventeenth century to a field of entirely unexpected experience, were in the nineteenth able to create new generalizations of the greatest theoretical importance. The steps leading to the *electromagnetic theory of light* are comparable with those leading to Newton's theory of gravitation. It represents in itself the second major unifying hypothesis which gave nineteenth-century science its deceptively final character.

The fourth section recounts the central advance of eighteenth-century science which resulted in bringing the field of chemistry, previously shared between blind empiricism and mystical alchemical theory, into the range of rational quantitative science. The *pneumatic revolution* associated with Priestley and Lavoisier represents the first large-scale extension of science beyond the region cultivated by the Greeks. Its overwhelming importance in human history lies in the fact that it was also the first in which science entered, in a positive and profitable

way, into a major productive industry. The subsequent close association of chemistry with the textile industries, with the passage from bleach and dyes to explosives and drugs, is the theme that accompanied and inspired *organic chemistry* in the nineteenth century.

Finally, from the vast field of biological sciences I have tried to bring out two or three leading threads which determined directions of advance. Here we have, on the one hand, agricultural and medical preoccupations which led ultimately to *microbiology* and to Pasteur's germ theory of disease. On the other hand, there is the passionate controversy on creation that was to lead through geology and natural history to Darwin's establishment of organic *evolution*. There can be no doubt that of all the great achievements of nineteenth-century science, including the magnificent generalizations of physics, only evolution is comparable in importance to the Copernican–Galilean dethronement of the earth as the centre of the universe. Henceforth man himself found his place in Nature. Only by recognizing that he was an animal could he learn how different from his ancestors the operations of society and civilization had made him. With the acceptance of evolution the last link with the Aristotelian world-picture was snapped; but the logical implications of a man-made world in the place of a celestial providential mechanism had yet to be drawn—a task that was to prove too difficult in the framework of capitalist society.

By focusing attention on the major scientific and technical advances of the period, I inevitably over-simplify the picture and am forced to leave out whole sequences of topics that would be needed for a comprehensive treatment. There is, however, no reason to believe that the story they would tell would be of a different kind. I have said, for instance, little or nothing about the great development of optics that set in at the beginning of the nineteenth century, involving the discoveries of polarization and diffraction that led to the reappearance of the wave theory of light, nor about spectroscopy and spectral analysis. These developments were to multiply the number of instruments available to other sciences, to transform chemistry and astronomy, and, in the next century, to provide a clue to the structure of the atom (p. 522). The story of optics abounds in examples of the interplay of scientific and economic factors even in the nineteenth century, before the days of the cinema

and television, but there is no space to tell of them here. The discussions in the sections which follow should, however, show sufficient of the types of interaction to cover those of the fields which are not treated.

9.1—*HEAT AND ENERGY*

The study of heat and its transformations was one of great intellectual, and even greater technical and economic, importance for the development of modern civilization. Originally, it was merely an extension of observations of Nature, of feelings of warmth and cold, of the operations of cooking, of the changes of the weather. There had been plenty of early speculations about heat. It was clearly connected with both life and fire, as also with violent action.

The Ionian philosophers had, following even earlier legends, brought in heat and its opposite cold as the causes of the evolution of the universe—heat expanding and vaporizing, cold congealing and hardening. Aristotle, especially in his meteorology, fixed the doctrine of the qualities of hot and cold, which, with wet and dry, determined the canonical four elements of fire (hot, dry), water (cold, wet), air (hot, wet), and earth (cold, dry) (p. 132).

This doctrine, a fusion of chemistry and physics, was engraved for millennia in human thought, as much in China and India as in Europe. The doctrine of antagonistic elements was particularly important in medicine and seemed to be supported by the experience of chills and fevers. Indeed it is from medicine that came the first elementary ideas of heat measurement. Heat and cold were supposed each to be ranked in four *degrees* or steps, the first just perceptible, the fourth mortal.[8.19] The object of heating or cooling medicines of the first, second, or third degree was to correct and temper its opposite, hence the idea of *temperature*.

This philosophical medical doctrine survived and took new life in the Renaissance. Bacon, following Telesius, had even made the antithesis of heat and cold a central feature of his philosophy (p. 306). From the very earliest times heat was associated with the movement of airs and vapours, and it was largely through its connection with the pneumatic discoveries of the seventeenth century that it left the orbit of qualitative philosophy to enter that of quantitative science. Galileo had

constructed an air-expansion thermometer, and such thermometers, together with Torricelli's barometer, were used for observation of the weather.[4.13]

The evolution of the steam-engine

The line of advance in the quantitative study of heat was not, however, to lie through such investigations, but along the practical road of the utilization of the power of expansion to make heat do useful work. All through the seventeenth century the idea of "raising water by fire", fascinated ingenious projectors (p. 330). The problem was how to combine two ideas, both old, into a practical engine: first to fill an empty space with water by suction (or vacuum), and then to expel the contents by pressure exerted by expanding air, steam, or gas. De Caus (1576–1626), a designer of the garden waterworks so favoured in the sixteenth century, solved the problem practically even before the vacuum was realized. He lit a fire under an almost empty vessel of water connected by a pipe to a well; when it had boiled away and was full of steam he took the fire away and closed the steam vent, and water was sucked up to fill the empty space. Though scarcely practical, this contained the essential principle of a vacuum engine, but until van Guericke's work (pp. 329 f.) its action could not be fully understood. Most of the scientists working on vacua had some idea of a practical engine but lacked the mechanical ability to make one that would work. The man who came nearest to it was Denis Papin, assistant to Huygens and Boyle in succession, who drew up the specifications of such a machine but could not raise the money to make it. He died in poverty in London. We have a pathetic letter from him to the Secretary of the Royal Society in 1708 asking for a sum of fifteen pounds for a "considerable experiment," with the Society's answer that it could not loan money unless assured of success in advance.[4.11.38]

The man who first succeeded in designing and financing a workable fire-driven pump was Captain Savery (1650–1715) of the Royal Engineers, who used two vessels alternately filled with steam to drive water out and then cooled to draw up more water, a method still in use in the "pulsometer" pump. Savery was no ordinary projector. He was fully aware, as his Patent Application entitled *The Miners' Friend* shows,[5.74] of the possible importance of the steam-engine, especially for draining mines,

where there was the greatest need for heavy continuous work. There he says:

> To the Gentlemen Adventurers in the Mines of England.
>
> I am very sensible a great many among you do as yet look on my invention of raising water by the impellent force of fire a useless sort of a project that never can answer my designs or pretensions; and that it is altogether impossible that such an engine as this can be wrought underground and succeed in the raising of water, and dreining your mines, so as to deserve any incouragement from you. I am not very fond of lying under the scandal of a bare projector, and therefore present you here with a draught of my machine, and lay before you the uses of it, and leave it to your consideration whether it be worth your while to make use of it or no . . .
>
> For draining of mines and coal-pits, the use of the engine will sufficiently recommend itself in raising water so easie and cheap, and I do not doubt but that in a few years it will be a means of making our mining trade, which is no small part of the wealth of this kingdome, double if not treble to what it now is. And if such vast quantities of lead, tin, and coals are now yearly exported, under the difficulties of such an immense charge and pains as the miners, etc., are now at to discharge their water, how much more may be hereafter exported when the charge will be very much lessen'd by the use of this engine every way fitted for the use of mines?

Nevertheless, Savery's engine laboured under several practical disadvantages, and its main value was to show that the problem could be solved. A more successful and practical engine was made in 1712 by the ironmonger Thomas Newcomen of Dartmouth, who used a piston which was depressed by condensing steam in a cylinder connected directly to a low-pressure boiler. Newcomen's engine did not, like Savery's, need to be built at the bottom of the mineshaft, it required less attention, and, not depending on high steam pressure, it was much safer. Its introduction marked the first stage in the translation of the scientific principle of atmospheric pressure into a machine that could be built by practical men and would not only work but also pay (Fig. 12, p. 377).

The fact that, as far as we know, Newcomen had no scientific training or connections [5.10.611] is among the reasons that caused R. S. Meikleham in 1824 to repudiate the view that the steam-

engine was "one of the noblest gifts of science to mankind." "There is no machine or mechanism," he asserted, "in which the little the theorists have done is more useless. It arose, was improved and perfected by working mechanics—and by them only." [5.58] These two extreme views as to the share of science in the origin of the steam-engine are not incompatible. It is doubtful whether the radical idea of vacuum pumping would ever have occurred to a mechanic, at least it did not before it occurred to a scientist; on the other hand, no scientist either had or could command the skill to solve the, no less essential, problems of making a working engine. As the sequel shows, the repeated combination of radical scientific ideas and experienced craftsmanship was needed in the further development of engines.

It says much for Newcomen's ingenuity that no radical improvement in his engine was made for nearly seventy years, and that some of the engines themselves ran for more than a hundred. But it was limited in its use, its action was too irregular for anything but pumping and blowing, and it consumed enormous quantities of coal. Its further development had to call on an injection of new ideas from the side of science, in particular from the creation of a quantitative science of heat.

Specific heat and latent heat: Joseph Black

Heat began to become a quantitative science with the gradual expansion and increase in scale of the industrial operations which made the largest use of it. It grew out of the scientific appreciation of the experience of the distillers and salt-makers, who were accustomed to boiling and condensing liquids on a large scale, and then out of that of the makers and users of the early steam-engines.

Dr Black, whose contribution to chemistry was to set off the pneumatic revolution (p. 448), was also the originator of the new view of heat. His approach was in the first place a medical–physical one. He was concerned with elucidating the nature of the element fire or heat that could pass through vessels and affect their contents. He found that different substances were heated to different degrees by the same amount of what he called the "matter of heat." This he discovered by the method of mixtures, which had first been used by Jean Morin (1583–1656) [5.60]—still working on the Arabic idea of four de-

grees of heat balancing four degrees of cold—and carried it to the point of establishing the heat capacity or *specific heat* of different substances. It was at this point that he reflected on the fact that snow and ice took time to melt—that is absorbed heat without getting hotter—and that the heat must be hidden or *latent* in melted water. He next measured the large latent heat of steam, which is reflected in the fact, long known in the distillery trade, that it required a very much greater amount of heat to boil water away than to raise water to the boil. Further, the heat absorbed in boiling was recovered when the steam condensed again in the worm of the still, where the application of much cold water was needed to get rid of it (Fig. 8, p. 263).

James Watt: the separate condenser

The first practical application of the discovery of latent heat was to be made by a young Glasgow instrument maker, James Watt,[5.26] who was charged with repairing a model Newcomen engine for the university (note here again the reciprocal action of technique on science). He found that the trouble was due to the steam lost at each stroke by condensing in the cold cylinder. Black gave him the explanation in terms of his newly discovered latent heat, and not long after Watt hit upon the idea of condensing the steam separately. This invention of the separate condenser in 1765 was crucial for the development of the steam-engine, as it made it immensely more efficient. The condenser was only the starting point of Watt's improvements.

Matthew Boulton: the Soho Engine Works

Before a saleable engine could be made Watt had, after a relative failure in Roebuck's Carron works, to go into partnership with great Matthew Boulton, the Birmingham manufacturer (p. 373), and make use of the resources of the growing metal industry of the Black Country before the steam-engine could be turned from an idea into a reality, for, as Watt himself admitted with unconscious irony, "the Scots were naturally incapable of becoming engineers." Particularly valuable were the services of John Wilkinson's cannon-boring machinery for providing true cylinders. By introducing the combination of flywheel, throttle, and centrifugal *governor*, Watt made an engine capable of driving machinery at steady speed even against very variable loads. This device in itself is the

first example of feed-back or *cybernetic* control in industry (p. 548). Appearing at the very outset of the great Industrial Revolution, it was a portent of the *automatism* characteristic of the second industrial revolution of the twentieth century.*

Until Watt's time steam-engines were only exceptionally used for mines well away from the coalfields; the Newcomen engine, even when improved by Smeaton (1724–92), was a paying proposition only in pumping coal-mines, where coal was naturally extremely cheap. But with the more efficient and steady Watt engine the products of the whole field of heavy-metal mining in Cornwall and, later, the power for the industrial textile mills, which were spreading all over the country, became easily available and cheap.

After a great struggle, for there were many economic and technical difficulties to overcome, the steam-engine won its way into every mining and and manufacturing district of Britain. Nor did it stop there, for Boulton believed in manufacturing for the whole world: steam-engines were set up in France, in Russia, and in Germany, most often by engineers from Britain.

The locomotive and the marine engine

The subsequent development of the steam-engine was conditioned by the technical and economic requirements it was called on to meet. Watt's engine was satisfactory enough for most mine and factory purposes, but it was expensive, heavy for the power developed, and still used too much coal. Where lightness and high power were needed was for a *locomotive* engine. Here the answer lay, as Trevithick had shown as far back as 1801, in a *high-pressure engine,* dispensing with the condenser altogether and blowing the exhaust steam into the air.[5.28]

The locomotive got off to a fumbling start. It grew up in its natural home in the coalfields on the *rail-way,* between pit and loading staithe. Before it could possibly pay there were innumerable problems to be solved, of drive, suspension, rails, permanent way, so that it is not surprising that here science had little part and that it was the self-taught colliery fireman's son, George Stephenson, who went farthest in solving all of them.[5.69] His decisive invention, made almost by chance, was turning the exhaust steam into the funnel and thus, by urging the fire, getting enough power to beat the horses and reach the phenomenal speed of twenty miles an hour. The acknowledged

triumph of the locomotive came with the Rainhills trials in 1829 of the new Liverpool–Manchester railway, where his Rocket took the prize.

The problem of adaptation to water transport was a very different one; there weight and size were not important but fuel economy was, for the steamer must carry its own coal. Indeed this limitation was to confine steamboats to river and coastal trade for most of the nineteenth century. The solution was found in the use of multiple expansion introduced by Hornblower (1743–1815) in 1781, but only slowly developed. No radical change, except the substitution of the screw for the paddle, was made until 1884, when Parsons' turbine revolutionized power production.

Interaction of economics and technique in the Industrial Revolution

The history of the steam-engine shows how the necessary conditions for the Industrial Revolution were both economic and technical; economic, in the sense that the textile industry grew up to provide the consumer goods for sale in an expanding market; technical, in the sense that the new engines were the only means of providing the coal and motive power, and ultimately the transport, without which the expansion of the textile industry would have been impossible.

For the most part the steam-engine was improved by practical engineers without any notable contribution from science. Its working did, however, attract the attention of many scientists who wished to understand it or even hoped to improve it. This study resulted in a much deeper appreciation of the laws governing the behaviour of gases and vapours—needed for drawing up steam tables—and was to lead to the new general conception in physics equating mechanical force and heat in theory, as the steam-engine already had in practice, in the common term of *energy*.

The establishment of caloric

Paradoxically, it was in France, where the steam-engine was a foreign importation, rather than in Britain, where it originated, that its operation as a means of transforming heat into work was first given serious scientific study. The primary difficulty lay in the traditional ideas that existed as to what heat meant. As we have seen (p. 413), heat was confused with fire; even the vitally important animal heat was attributed

to an invisible fire.[4.87] In the eighteenth century it was thought of as a material substance, Black's " matter of heat," later to be christened *caloric* by Lavoisier. Though attempts to weigh it failed, this only showed it was an imponderable fluid like electricity or light.[5.53] Lavoisier (p. 452) showed that this concept fitted very well with his idea of the generation of heat by chemical combination, particularly of combination with oxygen in a fire or in an animal body.

Nevertheless, an entirely different tradition, that heat was a form of motion and not a substance at all, also existed and was of even greater antiquity. Centuries of experience with the fire-drill and the forge had shown that force could be turned into heat; the steam-engine now demonstrated that heat could be turned into force. But it also needed the steam-engine, the engine for " raising water by means of fire," to bring out the quantitative relations between heat and work.

The early Newcomen steam-engine almost failed because the amount of work done by it hardly paid for the coals used, which were very expensive away from mines or tidewater. A horse could do it cheaper. Watt himself, in order to assess what he was to charge for the use of his engines, had measured the work a horse could do in foot-pounds per minute and had expressed the power of the engines in his new universal *horse-power*. The ingenious method by which the firm of Boulton and Watt managed to sell their engines was to offer to instal and service them free of cost; and to charge a royalty of one-third the saving of cost of either fuel or fodder over a Newcomen engine or horse-gin.[5.27]

The converse action of turning horse-power into heat was first demonstrated by Count Rumford in Munich in 1798 (p. 382). Always interested in heat, particularly in relation to its economical use, he had first noticed and then measured the heat given off in boring cannon. By showing that an indefinite amount of heat could be produced from a limited amount of matter he had effectively disproved the material theory of heat, but this was not enough to establish the alternative theory.

Carnot: the reversible heat-engine

The transformation of heat in the boiler of an engine to power in the flywheel, though amply made use of, could not for a long time be brought into the orbit of exact science.[5.3]

Each engine had its own conversion factor of coal burnt into work done, and this factor seemed to decrease as engines improved. No limit to efficiency seemed to be in sight, yet such a limit must exist or perpetual motion would be possible. It was such considerations that led Sadi Carnot, one of the great unrecognized geniuses of the nineteenth century, to his *Réflexions sur la Puissance Motrice du Feu* (1824). Sadi Carnot (1796–1832) was the son of Lazare Carnot, the "organizer of victory" of the French Revolution. He was trained as an engineer at the new École Polytechnique, and was one of the first to apply mathematical physical principles to the operation of the new machinery.

Carnot conceived the steam-engine as a kind of mill in which *caloric* at a high temperature flowed through the engine and left it in the condenser at a low temperature; provided none was lost in the process the maximum possible work would be done. The test for this was the reversibility of the engine, which, acting as what we now call a *heat pump*, could use the same energy in reverse to raise the same amount of caloric from the low to the high temperature. He showed that even under this optimal condition of *reversibility* only a fraction of the heat put in could be changed into useful work. In other words, work could be done only by the transfer of heat between different temperatures, equivalent to what was later called the *second law of thermodynamics*.

Carnot had gone further than this and had seen that some of the heat was actually transformed into work in the engine, and even found out how much. Before he could publish this knowledge, however, he died of cholera, and his great discovery of the mechanical equivalent of heat remained buried in his notebooks for fifty years. Meanwhile, his published work was also nearly forgotten till rescued by Clapeyron in 1832. Later, however, it was to form the fundamental basis of the new science of thermodynamics. The full elucidation of the relations between heat and work had yet to wait nearly another quarter of a century.[5.3] By that time it was long overdue.

The conservation of energy: Mayer, Joule, Helmholtz

The first to estimate the *mechanical equivalent of heat* was Robert Mayer (1814–87), a ship's doctor, in 1842. Soon afterwards it was also proposed by Joule (1818–89), a scientific amateur and the son of a wealthy brewer, and by von

Helmholtz (1821–94), a physiologist and physicist; and substantially the same idea, though not so clearly expressed, seems to have occurred independently to at least five other physicists or engineers. The approaches of the three principal discoverers were characteristically different. Mayer was led to the conception by general philosophical considerations of a cosmical kind. He was struck by the analogy between the *vis viva* (energy) gained by bodies falling under gravity and the heat given off by compressed gases. Joule was led to the idea first by experiments aimed at finding out how far the new electric motor could become a practical source of power. In showing that it could not, because all the power came from the burning up of the very expensive zinc in the battery that drove it, he was led to consider the quantitative equivalence of work and heat. This he communicated to the British Association at Cork in 1843, but received scant attention. The Royal Society refused to publish his paper in full, and Joule had to batter his way to recognition by ever more accurate experiments.[5.3]

Helmholtz in 1847, by an attempt to generalize the Newtonian conception of motion to that of a large number of bodies acting under mutual attraction, showed that the sum of force and tension, what we would now call kinetic and potential energy, remained the same. This is the principle of the *Conservation of energy* in its most formal sense, but it was important in that it reconciled the new doctrines of heat with the older ones of mechanics, a process that was to be largely completed by William Thomson, later Lord Kelvin, a friend of both Joule and Helmholtz, in his paper *The Dynamical Equivalent of Heat* (1851).*

However varied the approach, all the discoverers were influenced, and more directly than indirectly, by the atmosphere of the age of steam,[5.3] and particularly by the locomotive. As Mayer remarked: "It is in the locomotive that heat is distilled out of the boiler, turned into mechanical work in the moving wheels, and condensed again to heat in the axles, tyres and rails."

The principle of the conservation of energy, of which mechanical work, electricity, and heat were only different forms, was the greatest physical discovery of the middle of the nineteenth century. It brought many sciences together and it fitted very well into the trend of the times. Energy became the universal currency of physics—the gold standard, as it were, of changes in

the universe (p. 121). What had been established was a fixed rate of exchange between the different energy currencies: between the calories of heat, the foot-pounds of work, and the kilowatt-hours of electricity. The whole of human activity—industry, transport, lighting, ultimately food and life itself—was seen to depend on this one common term: *energy*.

The availability of energy

In the latter part of the century, however, the doctrine of energy which had seemed so optimistic was seriously modified by the realization that the second law of thermodynamics showed that it was not so much the quantity of energy in the universe but its availability that mattered, and that this was always decreasing. In the molecular terms of Maxwell, any system starting with fast (hot) molecules and slow (cold) molecules would end up with most of the molecules moving at intermediate speeds (tepid) or, in the expression of Gibbs (1839–1903), the muddled-upness (entropy) of a systém always tended to increase.

If the universe was treated as a whole, it appeared inevitable that the sources of heat would gradually wear themselves out into a universal tepidness, the so-called " heat death " of the universe. Kelvin, the great propagator of this idea, seemed almost to rejoice in this prospect of a universal mediocrity. Coming nearer home, he was able to prove that the sun could not have been shining indefinitely, and thus that the earth could not have existed for more than a few hundred million years. This was far less time than the geologists required to explain evolution, but the authority of the physicists carried the day. They were wrong, for this prediction, like many others, was doomed to be violently upset by the discovery of new sources of power in the atom of an altogether greater order of magnitude. It is only fair to Kelvin to point out that he guarded himself against this by qualifying his predictions: " Unless sources now unknown to us are prepared in the great storehouse of creation." [5.88]

The philosophy of energy: Mach, Ostwald, and the new positivism

It was in this period, too, that the knowledge of thermodynamics began to reach into chemistry and even into biology, thanks largely to the works of le Chatelier (1850–1936) and Gibbs (1839–1903).[5.6] It seemed for a while as if the whole of

natural phenomena could be explained in terms of simple observables of mechanical energy and heat, and this, in the hands of philosophers like Mach and chemists like Ostwald, seemed to promise an escape from the awkward materialism and radicalism of the atomic theory.

A new positivism appeared which stated that matter and physical hypotheses such as atoms were no longer necessary, and that the whole of science could be deduced directly from elementary observations. The kinetic theory of heat, evolved by Maxwell in 1866 and implying the existence of atoms, was in contradiction to this tendency. Maxwell's atoms, however, were entirely hypothetical and new evidence was needed before they could be accepted as measurable and countable material objects.

9.2—*ENGINEERING AND METALLURGY*

One dominant feature of the eighteenth and nineteenth centuries was the triumph of the machine. Here, however, the part of science is still a relatively minor one. For both in engineering and metallurgy the technical element, based on the tradition of hand work, and the economic element, based on profitability, were predominant. Nevertheless the scientific element was always active and grew steadily in importance, preparing the way for the lead it was to take in the twentieth century.

The history of engineering in its great creative phase of the eighteenth and nineteenth centuries marks a continuous interplay between the growing requirements of commerce and industry, and the new means of operation—machinery, engines, materials, which created new possibilities of profitable use. It was the need for more yarn and more cloth that led to the first introduction of textile machinery; the need for more coal, to the first steam-engines; the need for cheap transport of ever more abundant goods led to improvement in ports, canals, roads, bridges, and to the radical innovation of railways (p. 389). However, no sooner was some new mechanism or material developed to meet these needs than new ventures and extensions to other hitherto impossible or unthought-of uses became possible. Thus the steam-engine, first developed for pumping, was adapted next to blowing furnaces and hammering iron, and then to supplant the water-wheel in driving machinery.

Later still, mounted on a boat or a wagon, it became automotive and gave birth to the steamship and railway. In a similar way, cheap iron and cheap steel, called into being by specific needs of machine construction, provoked a revolution in the construction of further machines, vehicles, ships, and buildings.

The engineers

At every stage in the development of machinery and metals the handicraftsmen were busy trying out new devices and absorbing as much science as they could turn to use; and the scientists were perforce learning the trades so that they could understand the principles underlying them. The process is one we can study through the medium of the biographies of the engineers of the great period from 1750 to 1850, and here we are fortunately well supplied through the work of the great historian of industrial Britain, Samuel Smiles,[5.78–80] and also that of a new generation of more scholarly historians such as Dickinson [5.26–28] and other members of the Newcomen Society. In Britain, for long the centre of the Industrial Revolution, the engineers for the most part began as simple workmen, skilful and ambitious but usually illiterate or self-taught. They were either millwrights like Bramah, mechanics like Murdock and George Stephenson, or smiths like Newcomen and Maudslay. Hardly separable from them, except for their closer connection with science, were instrument-makers like Smeaton and Watt, artists like Nasmyth (1808–90), or mining engineers like Trevithick. In France, where the workshop played a smaller part and the State and the military schools a larger one, the school-trained engineers predominated: men like Jars, Monge, Poncelet, Fourneyron, Sadi Carnot, and Marc Brunel (1769–1849), a gift of French engineering to Britain. In the later period, after 1850, scientific predominance is more marked, and with it the new importance of Germany in major developments; Britain has only Parsons to balance against Germany's Siemens family, Otto, and Diesel.

The major trends of the whole period of the Industrial Revolution were in the invention of ever more ingenious mechanisms and in the steadily improved performance of machines and structures. Except where new physical principles were involved for the first time, as in new heat-engines and electrical machines, neither made much demand on science.

The design of mechanisms, mostly in imitation of a human workman's activities, involved a practical kind of mechanical mathematics too complicated to be learned at school, and stemming rather from the traditional ingenuities of the clock-maker and locksmith. To be successful, however, this had to be matched with a shrewd appreciation of the needs of the industry of the time and a knowledge of where labour saving was likely to be possible and profitable. As these kinds of judgment rarely ran together, the exploiter of inventions—like Arkwright (p. 368), the great promoter of the Industrial Revolution in the cotton trade—usually tended to supplant the mere inventor, who was as likely as not to be ruined; but the machines got built. From 1750 onwards the combination of inventor-exploiter was invincible. Ingenious mechanical substitutes for human hands spread from the textile industries to hundreds of others, both in the manufacture of consumption goods and in the metal and machine industry itself. They even invaded the oldest traditional occupations of agriculture and food processing, especially in America, where, despite slavery, good land was more abundant than were people to work it. Varied as they were and great as was their effect on the growth of civilization, the mechanisms of the eighteenth and nineteenth centuries were combinations of old principles, rather than applications of new as were to be those of the twentieth, and consequently they neither owed much, nor gave much, to science.

Efficiency and utility: the turbine and the internal-combustion engine

The improvement of the *performance* of machinery and engines, almost exclusively steam-engines, was to be the task of successive generations of engineers. Through most of the period it was largely a question of adapting the engine to its various uses, and steadily increasing its power yield per unit of weight of fuel or prime cost, by detailed improvements and better design. In the latter part of the nineteenth century Carnot's ideas, and the thermodynamics built on them, gradually permeated the engineering world; but these ideas were more effective in the revolutionary sense of leading to the turbine, the internal-combustion engine, and the refrigerator rather than in improving the old reciprocating engine.

The new developments were to split the world of power generation into two more manageable and adaptable halves.

The *internal-combustion engine* was to lead to the light power unit, to the motor vehicle, and later to the aeroplane; the steam *turbine* to giant ship propulsion and to the generation of distributable electrical energy. Though products of the nineteenth century, they were to find their field of effectiveness only in the twentieth (p. 561).

Engineering construction: the machine tool

The opportunities for profit arising from the use of machinery called into being the machine-building industry; and this in turn was to create a revolution in handicraft, taking the mechanical process one stage further and using machines to make machines. Of these the first and most important were Maudslay's slide-rest and screw-cutting lathes (Fig. 13).[1.31; 5.10*] The debt of this revolution to science was small, and limited to the control of eye and fit judgments by a more rigorous application of geometry, such as Maudslay's plane and micrometer and Whitworth's standard screws. Here the old tradition of the millwright and clockmaker blended continuously into that of the new *mechanical engineer*. The conditions that made this possible was the availability of metals—first iron and then steel—capable of taking the new precise shapes, and that of the mechanical power to work them. Only towards the middle of the nineteenth century did the tasks of engineering begin to get beyond the scale of resources of the Ancients. Nasmyth's steam-hammer broke once and for all the traditions of Vulcan's forge, and the building of machines became a machine-sized and no longer a man-sized job.[5.63]

Though the actual production of precisely finished metal parts owed little to science, depending as it did on the smooth performance of machines, it was to be the way in which mechanical engineering could itself become scientific. The most elaborate mathematical applications of Newtonian mechanics in the eighteenth century were of little use to practical engineers, because machinery could not be made accurately enough except by the highest craftsmanship and for quite exceptional machines like clocks. Even for the vital needs of war, guns could not be made with sufficiently smooth and uniform bore to enable any serious use to be made of the well-established theories of ballistics.[4.60] With precision metal-cutting all this changed, and the performance of mechanical devices could be calculated from the drawing-board with some

chance of predicting performance in advance. It was also to open the way to the use of interchangeable parts, and thus to the mass-production methods of the twentieth century. The first anticipations of this were Eli Whitney's (1765–1825) musket factory in 1800 and the factory for naval stores which Sir Samuel Bentham, Jeremy Bentham's brother, set up in Russia in 1784, and which afterwards led to the British Admiralty block factory in which the machines were made by Maudslay. Both were, significantly, technology for war.

The metal revolutions

The demands for new machinery, particularly the heavy machinery for mines and later that for railways, ships, and buildings, not to mention the ever-recurring military claims, could only have been satisfied by an ever-increasing flow of metal, and of metal of better and better quality. The ready availability of iron and steel, and the revolution in metallurgical technique that this entailed, were factors in the Industrial Revolution of comparable importance to the invention of textile machinery and to the steam-engine. Here again, as in the case of machine-building, the metallurgical revolution owed much to practical men and little enough to science until the crucial stage in large-scale steel production towards the end of the nineteenth century.

The metallurgy of iron and steel had been practised as a craft for at least 3,000 years. The skill of medieval smiths, of both the East and West, could hardly be improved on. But their products, carefully hand-made, were costly and the quantity available was limited to supplying the fairly static demands for axes, horseshoes, ploughshares, arms, and armour. The new demands for artillery for the wars of the sixteenth century strained production in western Europe to the limit, even after the radical invention of cast iron (p. 283). For basic iron production still depended on wood charcoal, and the progressive exhaustion of supplies drove the iron industry into the forests of Sweden, Russia, and America.

The age of iron

It was this limitation, in the face of the ever-increasing demands of growing commerce and industry, that forced the revolutionary transition from wood charcoal to *charked* pit coal or *coke* in the early eighteenth century, and this completely

established the dominance of the coalfields over the forests, for coal as a domestic and industrial fuel had already supplanted wood. Though the possibility of using coal for making iron had long been appreciated, as we have seen (p. 285), actual success turned on the solving of numerous physical and chemical problems quite beyond the science of the day. They had to be solved in practice together with the overriding problem of selling at a profit. The failure of the first projectors lay largely, as in Sturtevant's case, with over-ambitious financing and attempts to enforce monopolies (p. 285 f.).

Only the perseverance and the probity of the Quaker family of the Darbys of Coalbrookdale [8.56] overcame all these obstacles, and by the middle of the eighteenth century had inaugurated the era of cheap cast iron. The price of pig iron in 1728 was £12 a ton, by 1802 it had fallen to £6.[5.2] But cast iron had its limits. True, rails, pillars, bridges, wheels, engine cylinders could be made of it, but not tools or the working parts of engines. Wherever tension or toughness was needed, wrought iron had to be used, and steel if hardness and springiness were needed as well. Partial solutions to the production of these were found with Huntsman's crucible steel, 1740, and Cort's puddling and rolling process, 1784, both inventions involving much intelligence but owing nothing to official science. Earlier in the eighteenth century Réaumur's work on *L'Art de Convertir le Fer Forgé en Acier* (1722) revealed both the limitations and the possibilities of the science of the time. Réaumur had been able by careful experiment to solve the mystery of the steel-makers, a secret guarded from the time of the Chalybes (p. 102), that steel is iron containing not too much and not too little carbon. He found he could make it by melting cast iron and wrought iron together. He published his results, and in doing so penned one of the noblest defences of freedom of scientific publication,[1.3.151] but no one took any advantage of them. Either the ironmasters could not read or they found Réaumur's recipes impracticable.

Throughout the late eighteenth and early nineteenth centuries the production of iron went on at full blast, with that of steel lagging far behind. Improvements were all in the direction of speeding up the process by the use of a compressed and then a hot blast introduced by Neilson (1792–1865), a gas-works chemist.[5.4] They involved little more than the use of the new mechanical powers to transform an age-old process.

The age of steel: Bessemer, Siemens, Gilchrist Thomas

The decisive break came with the radical innovations of Bessemer in discovering a way of making cast steel on a large scale. In his converter, air, blown through melted pig iron, burns away the carbon, producing enough heat to keep the resulting steel melted. This may be called a semi-scientific result, for though it lacked a theoretical foundation it was arrived at by experimentation. Bessemer was not a scientist but a typical inventor, who knew just enough and not too much science and had a little experience of metals, but not in the iron industry.[5.3; 5.87] It is notable that neither the ironmasters nor the professors of metallurgy ever proposed any such crazy processes; they knew enough to be sure that they would not work.

Soon after the appearance of Bessemer steel in 1856 an older process took on a new lease of life through the application to the open-hearth or reverberatory furnace of Siemen's principle of heat regeneration, by which the temperature can be raised by using the spent hot gases to heat the incoming air. In this way large charges of steel could be melted and Réaumur's process could be used starting from pig, scrap, and ore. From 1867 on the open-hearth became a serious rival to the Bessemer converter.

Both processes had one serious limitation: they were usable only with relatively pure iron ores (which were not of widespread occurrence) such as those of Sweden, Spain, and Lake Superior. Before they could be used for the more abundant sedimentary ores of Cleveland and Lorraine one final improvement had to be made: the introduction of the basic lining to absorb the deleterious phosphorus. This was the discovery of Gilchrist Thomas in 1879, and is significant not so much because of the magnitude of its consequences, but because it was scientific through and through.[5.3; 5.87] Though Thomas had to earn his living as a police-court clerk in Stepney, he was a master of metallurgical theory; he understood exactly what he was trying to do and the experiments he made in a London cellar could be translated successfully within three years to full-scale production. His work is a portent of the industrial research of the next century.

These three processes together inaugurated the age of steel, first rapidly completing the displacement of wood as a structural material in engineering, and then that of cast iron for rails,

ships, and guns. Cheap steel was the basis on which the imperialism of the late nineteenth century was to be built, with its emphasis on ocean commerce, the exploitation of tropical colonies with railway and port developments and its ever more costly preparations for naval and land warfare.

9.3—*ELECTRICITY AND MAGNETISM*

The first new science to arise after the end of the Newtonian period was electricity, in part because it was almost the only aspect of physical science to which Newton himself had not devoted his attention, and accordingly where his great prestige did not frighten off lesser investigators. Electricity had had a long and legendary past. From the earliest times we know of, men had treasured amber and probably noticed its power, when rubbed, of attracting small bodies. It was natural to make the analogy between this and the much stronger power of attraction of the magnet; natural, too, to assimilate both of them into the general magical thinking of ancient times. The doctrine of affinities and attractions, the whole idea of *virtue* residing in a special kind of substance and being evoked by appropriate treatment, was exemplified in amber and even more so in the magnet, because of its magical property of transferring its virtue to other objects by touching them.

The science of magnetism, however, only began when this virtue could be used to good purpose, as in the mariner's compass (p. 235). We have already discussed some of the steps by which the study of the compass led through Peter the Pilgrim and Robert Norman to Gilbert and the beginning of the scientific study of magnetism (p. 299).

Gilbert's *De Magnete* was not only concerned with magnets; it included a generalization of the attractive principle to cover that of amber and the invention of the first electrical instrument, the balanced pointer or versorium, the later descendants of which, electroscopes and galvanometers, were to give so many pointer readings to science.

Early electricity: effects of friction

Although, as we have seen, Gilbert's magnetism was to be an inspiration to the formation of a theory of gravitation, his electrical experiments were hardly developed beyond the point

at which he left them throughout the whole of the great experimental period of the seventeenth century. In its early stages it did not seem to promise any profitable application. It was a philosophic toy and as such lay a little outside the interests of the time, which were turned so largely to mechanics and the vacuum. Nevertheless, some experiments were made in connection with the vacuum which provided the link with the great developments that were to come later. Von Guericke, the inventor of the vacuum pump, in about 1665 developed the rotating globe or sphere from which, by friction, he drew sparks. This was to be the type of the electrical machines of the next hundred years; but for him it was a model to illustrate his cosmological theories. Picard (1620–82) noticed in 1675 that a barometer shaken in the dark gave a green light—the mercurial phosphorus. This roused the interest of Hauksbee (d. *c.* 1713), Newton's assistant, at the beginning of the eighteenth century. He showed that friction at the same time as generating electricity could produce luminous effects in a vacuum—the forerunner of all our fluorescent lighting—but he made no advance in understanding how they occurred.

Gray: conductors and non-conductors

Another follower of Newton, Stephen Gray (*c.* 1666–1736) [8.12] pursued similar experiments which led him in 1729 to an illuminating discovery of the transmission of electricity. Almost by accident to start with, but then logically step by step, he was led to the idea that electricity, produced by rubbing a glass tube, could be communicated over large distances. His first observation was that the corks he had put in the ends of his tube attracted small pieces of paper or metal. Next he thought of sticks at the end of the corks, then knobs at the end of the sticks, then balls attached to strings, all of which attracted just as well. Finally he led the electricity out of his room by packthread on silk loops right round the garden and produced what was effectively the first electric telegraph. The fundamental discovery he had made was that electricity was something that could flow from one place to another without any appearance of movement of matter—that it was weightless, an *imponderable fluid*. Electricity could be held in the bodies like glass or silk in which it was generated. These he called the *electrics*—what we now call non-conductors or dielectrics—and electricity could not flow through them. On the other

hand electricity flowed through metals or damp string and could not be generated in them. They were the *non-electrics* or *conductors*.

Dufay: two kinds of electricity

The news of these experiments, so simple and interesting, soon got round and began to make electricity a fashionable and amusing subject which a few amateurs here and there followed up. Dufay in France found in 1733 that there were two kinds of electricity, vitreous and resinous, according to whether amber or glass was rubbed. Many people began to build electrical machines to try all kinds of experiments and even to exhibit them for money.

The Leyden jar and the electric shock

A fairly obvious idea was that of trying to store the electric fluid in bottles. In 1745 von Kleist (d. 1748), a Pomeranian clergyman, attempted to pass electricity into a bottle through a nail. Touching the nail while holding the bottle in his other hand he received what must have been the first artificially produced electric shock. Some months later, and apparently independently, Musschenbroek (1692–1761) reported a similar experiment from Holland. As he was a scientific apparatus maker, with numerous connections in the learned world, his name is usually associated with what is still called the Leyden jar.

This discovery had a literally explosive effect. Everybody wanted to try the shock and to see it tried on other people. Electricity became the high fashion in courts. The king of France organized the electrification of his whole brigade of guards, who were made to jump in unison by shocks from batteries of Leyden jars.

Franklin: positive and negative electricity

So much was electricity the rage that Franklin (p. 371), in remote Philadelphia, heard of it and sent for some electrical apparatus. With his robust common sense and apparatus of his own devising, he was able to see through the confusions of previous electric experiments and proposed the explanation, which holds to this day, that there are not two kinds of electricity but one. He imagined it as a kind of immaterial fluid existing in all bodies, undetectable as long as they were saturated with it. If some was added they became positively charged, if some

was removed—negatively. The tendency of the electric fluid to reach its true level was the cause of electric attractions and, when strong enough, of sparks and shocks. If we replace the fluid by practically weightless electrons and change the sign of the charge, $-$ for $+$, for it is a negatively charged body that has an excess of electrons, Franklin's explanation becomes the modern theory of electric charge.

The lightning conductor

This simplification, together with an explanation of the action of the Leyden jar, were Franklin's serious contributions to electrical theory and immediately established his scientific reputation. But what really impressed the world at large was his appreciating the analogy between the electric spark of the laboratory and the lightning which he snatched from the sky with his kite and showed that it was electricity. From this he, in his practical way, immediately drew the conclusion that it would be possible to prevent the damage due to lightning, particularly heavy in the New World, by the *lightning conductor* which he tried out in 1753. With this invention electrical science became for the first time of practical use. Franklin's patriotic, or rebel, tendencies had a curious by-effect in England, where in 1780 King George III insisted that the lightning conductors at Kew Palace should have round knobs, instead of the sharp points Franklin had proposed, and Sir John Pringle (1707–82), the President of the Royal Society, who could not agree, was induced to resign. A contemporary wit summed up the controversy with this epigram:

While you, great George, for safety hunt,
And sharp conductors change for blunt,
  The nation's out of joint.
Franklin a wiser course pursues,
And all your thunder fearless views,
  By keeping to the point.

Coulomb and the law of attraction

Despite all these advances electricity and magnetism remained mysterious imponderable fluids, and their quantitative study could not begin until some method could be found of measuring them. This was the work of Coulomb (1738–1806) in 1785, undertaken, significantly, with the object of improving the mariner's compass.[5.10] He found a way of suspending the needle on a fine fibre and used it to measure

the forces between magnetic poles and later between electrical charges. This is the torsion balance, the prototype of most sensitive electrical instruments of today, which was also independently developed by Michell (1724–93) and used by Cavendish (1731–1810). With it Coulomb established what had already been surmised for some years, that the forces between magnetic poles as well as those between charges of electricity obeyed the same laws as those of gravity, that is, a force proportional inversely to the distance. The same conclusion had already been seen to follow from the observation, made by Priestley in 1766 and more carefully by Cavendish in 1771, that no charge was to be found *inside* a charged conductor. These experiments enabled the whole apparatus of Newtonian mechanics to be applied to electricity, but with this difference: that in electricity repulsive as well as attractive forces were to be found.

Animal electricity: Galvani

The immediate development of electricity was not, however, to lie along this quantitative line. Once again, as in the case of the Leyden jar, human and animal sensation came in to reinforce and direct the progress of physics. Acute observers had noticed that there was a close similarity between the shocks given by the Leyden jar and those produced by various electric fishes, particularly by the electric ray (or torpedo—the " putter to sleep "). Cavendish in 1776 had actually made a working model torpedo out of leather, connected to a battery of Leyden jars.[5.57b] This led to the concept of animal electricity, and many confused and ineffectual attempts were made to discover it until in 1780 Galvani (1737–98), professor of anatomy at Bologna, happened to make experiments in which animal preparations were mixed up with electrical apparatus. He noticed that several pairs of frogs' legs contracted whenever there was a spark. It was six years, however, before he observed that it was not really necessary to have the electrical apparatus, that the frogs' legs would contract if two different metals in contact were applied to the nerve and the muscle.

The electric current and the battery: Volta

Galvani had in fact discovered current electricity but he did not recognize it. His interest in the physiology of nerves caused him to see his experiments rather as proof of animal electricity.

It required the more logical mind of his compatriot Alessandro Volta (1745–1827), Professor of Physics at Pavia, to understand what he had done. In 1795 Volta showed how to produce electricity without any animal at all by simply putting two different pieces of metal together, with liquid or a damp cloth between them, and he thus produced the first *electrical current battery*.[4.81]

The progress of electricity in the closing decades of the eighteenth century is a clear example of the converging effects of all the sciences, and the particular stimulus given in that time of revolution to everything at once novel and useful. On account of its physiological effects electricity interested doctors and quacks looking for new methods of treatment. Among them was Dr John Graham, whose Temple of Health was presided over by Miss Emma Lyons, afterwards Lady Hamilton. At the same time, and also partly through the doctors, electricity was drawn into the service of the then culminating pneumatic revolution in chemistry (p. 447). In 1800 Dr Carlisle (1748–1840), a London surgeon, and his friend William Nicholson (1753–1816), an engineer, commercial traveller, and scientific publisher, used the newly invented battery to decompose water into its constituents—oxygen and hydrogen (p. 450). Thus they settled a crucial problem in chemistry and started the new sub-science of electrochemistry.

Galvanic batteries soon were as much a necessity for a well-equipped laboratory as batteries of Leyden jars had been fifty years before. But at first they were even more expensive, and only the wealthiest could build large ones. Thus it fell to Davy in 1802 to produce the new metals, sodium and potassium, by the use of the world's largest battery at the Royal Institution. These experiments brought electricity out of its isolation, as a set of peculiar phenomena, and linked it with the general body of science. It was beginning to show a promise of use as well as interest. The promise could, however, not be fulfilled for some decades, until a connection had been found between electricity and magnetism.

Except for the discovery that the electricity from the Galvanic cell and that from the frictional machine were of the same kind, though vastly different in quantity and intensity, the nature of the electric current was to remain shrouded in mystery for another twenty years. Currents from batteries were variable and unpredictable and it was impossible to subject them to

measurement until an entirely different effect of the current was discovered.

Electromagnetism

The multiple analogies between electricity and magnetism made physicists think that there must be some connection between them, but it was one very difficult to find. It was not until 1820, that through another accident at the lecture table, Oersted (1757–1851) in Copenhagen found that the electric current deflected a compass needle. He thus joined together, once and for all, the sciences of electricity and magnetism. One immediate consequence was the invention by Sturgeon (1743–1850) in 1823 of the electromagnet and its improvement by Henry (1799–1878) in 1831.[5,6] At one remove it led to that of the electric telegraph and the electric motor.

The deflection of the compass by the electric current also had enormous theoretical importance. In the hands of Ampère (1775–1836), Gauss (1777–1855), and Ohm (1787–1854) it led to the understanding of the magnetic fields produced by currents and of the way these flowed through conductors. Current electricity could now become a quantitative science and take over all the mathematical apparatus of mechanics. Nevertheless, in one important and puzzling respect the new laws differed from those of Newton. All the forces between bodies that he considered, acted along the line joining their centres; but here a magnetic pole was urged to move *at right angles* to the line joining it to the current-carrying wire. This was the first break from the simple *scalar* field theory, and opened the way to a more inclusive *vector* theory where direction as well as distance counted. It was these physical discoveries that were to give a new impetus to mathematics and to wean it from the now sterile adherence to the Newtonian tradition.

Accidental discoveries?

It is interesting to reflect on the sequence of apparently accidental discoveries that led to this stage of knowledge. At first sight it seems to reinforce the idea that science is entirely unpredictable and depends entirely on purely chance discoveries. Actually, now that we know the character of some of the relations between different aspects of Nature, we can see that it must have been extremely difficult in the long run not

to have hit upon them in one way, if not in another. Oersted, inspired by the unitary ideas of *Naturphilosophie*, had certainly been looking for the connection between electricity and magnetism for thirteen years, but his actual discovery was not the result of any deliberate planning. In this case, as there were so many people playing with electric currents and compass needles at that time, someone could hardly fail sooner or later to notice their interaction. Many probably did and thought no more of it. The difficulty in science is often not so much how to make the discovery but to know that one has made it. In all experiments there are a number of effects, produced by all kinds of extraneous causes, which are not in the least significant, and it requires a certain degree of intelligence or intuition to see which of them really mean anything. This is particularly so when there is nothing in existing theory to make one expect such events to happen, and even more so when, as is often the case, there appear to be perfectly good reasons for not expecting them. Sooner or later, however, if enough people concentrate on the field, someone will be found sufficiently observant, sufficiently broadminded, and sufficiently critical or sufficiently ignorant of orthodox theories to make the discovery (p. 543).

Michael Faraday: electromagnetic induction

Before the full interaction of electricity and magnetism could be understood, still one more decisive step had to be taken. It had been shown how electric currents produced magnetism; it remained to show how magnetism could produce electric currents. This discovery, though it had to wait for another ten years, was not, like Oersted's, accidental. It was the result of a deliberately planned research by Faraday. In 1831, in his fortieth year, and free from the restrictions that the somewhat jealous Davy put on his work,[5.5] Faraday showed that the relation between magnetism and electricity was dynamic and not static—that a magnet had to be moved near an electric conductor for the current to arise. This most crucial observation showed that not only was magnetism equivalent to electricity in motion but also, conversely, electricity was magnetism in motion. Thus both sets of phenomena could only be discussed in the new joint science of *electromagnetism*.

Faraday's discovery was also of much greater practical importance than Oersted's because it meant that it was possible to generate electric currents by mechanical action, and con-

versely that it was possible to operate machinery by electric currents. In essence the whole of the heavy electrical industry was in Faraday's discovery, but it took the greater part of fifty years before full advantage could be drawn from it (pp. 440 f.). Faraday himself had little inclination to move in the direction of practical application. This was not due to any other-worldliness; Faraday knew enough from experience of the world of business and government to estimate the time and trouble it would take him to bring any of his ideas to the stage of profitable exploitation. He felt he could make better use of his time.[5.18]

He was concerned, as his note-books show, with a long-range project of discovering the connections between all the " forces " that were known to the physics of his time—electricity, magnetism, heat, and light—and by a series of ingenious experiments he was in fact able to succeed in establishing every one of these, and to discover in the process many other effects the full elucidation of which has had to wait till our time.[5.32]

The electromagnetic field: Maxwell

Faraday was one of that rare class of physicists who had a visual and almost sensuous understanding of the forces with which he was dealing. His vivid imagination created the picture of electric and magnetic fields, equipped with lines and tubes of force, showing that whenever a tube of magnetic force cut an electric conductor it gave rise to an electric current, and conversely that the movement of electric tubes of force gave rise to magnetic fields. In this sense Faraday's work was complementary to that great mathematical synthesis of Newton, where fields and potentials took the place of attractions between geometrical points. The formal translation of Faraday's qualitative intuitions into precise and quantitative mathematical equations was the work of Clerk Maxwell (1831–79), who summarized in concise form the whole of electromagnetic theory—apart from the apparently wayward effects of electricity on matter such as occurred in electrical discharges and were to lead to the discovery of the electron (p. 517).

Electromagnetic waves

But Maxwell's equations did more: from their form it was possible to see that they could be fitted to expressions for waves of electromagnetic disturbance which would travel with a speed

suggestively near to that of light. The nineteenth century had already witnessed a great reversal in ideas on the nature of light. Newton had determined to his own satisfaction, and for 100 years no one had dared to question his authority, that light consisted of fiery particles travelling at great speed. In 1801 the physician Thomas Young (1773–1829) in England, and the physicist Fresnel (1788–1827) in France, had been forced, by a consideration of the interference and polarization of light, to go back to Huygens' view that it consisted of waves. After a sharp battle with worshippers of Newton they carried the day, and for 100 years the wave character of light was unchallenged. However, if the fiery particles were no longer needed, a medium was required to carry the waves, even through the vast emptiness of space, and the "luminiferous ether," which had the incompatible properties of being infinitely rigid and infinitely tenuous at the same time,[4.117] was called into existence to do so, to be "the nominative of the verb to undulate." But electricity and magnetism had also long been known to act through empty space. For them, equally intangible *fields* were created. Maxwell showed in effect that one single but still mysterious ether (p. 337) would do for all three. He had achieved a great condensation and simplification in physics from which important consequences were soon to follow.

One was the establishment of a new unity between sciences: the whole of light appearing as an electromagnetic phenomenon. Another was the inference that electromagnetic oscillations ought to give waves in the ether similar to those of light, but with much lower frequencies. Hertz (1857–94) demonstrated these in the laboratory in 1888, and they were later to become the basis of radio-communication.

With Maxwell's equations, electrical theory appeared to be so nearly complete that the future of physics seemed to hold only an extension and perfection of it. Actually, as we shall see in the next chapter, it covered only a small part of the phenomena of electricity, and the corpuscular unit of electricity, the electron, escaped the equations entirely.

The lags in the application of electricity

In order to present a coherent story of the development of electromagnetic theory it has been told as one logical sequence running right through the nineteenth century. But the growth

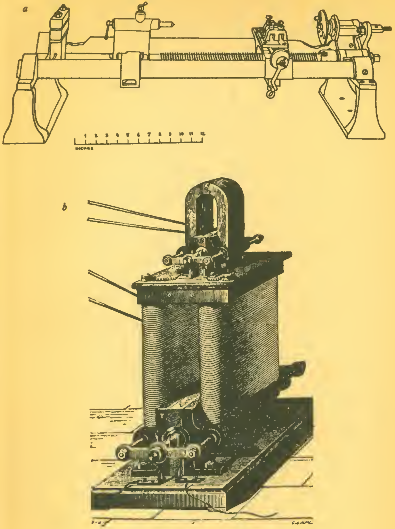


FIG. 13.—NINETEENTH-CENTURY TECHNOLOGY

(*a*) Sketch of Maudslay's original slide-rest, screw-cutting lathe, as preserved in the Science Museum, London (p. 427).

(*b*) Wilde's first *dynamo*, with separate exciting *magneto* for field-coils of magne (p. 442).

of electricity throughout that period had another and practical side that interacted continuously with the advance of theory.[5.3] From about 1830 onwards electricity began to contribute directly to economic life, first in the form of communication, then for electroplating, for light, and for power, with two new forms of communication—the telephone and wireless—thrown in at the end of the century. Electricity was indeed the first science to create an industry of its own without any dependence on tradition.

The process was nevertheless a slow one, for in spite of the legend of the alert entrepreneur capitalist seizing on new ideas and marketing them ahead of his competitors, there were in fact enormous practical difficulties in introducing anything that required development before it would pay. Both academic scientists and independent inventors were in constant straits to finance these developments. The only way it could be done was to produce anything that would sell quickly, and to finance each new development from the profits of the last. Very few people managed to surmount all the hurdles of an important application. Most were broken or discouraged, and there were innumerable false starts.

In the process of converting the discoveries of the laboratory into the products of a profitable industry, four main stages can be discerned, each concerned with a different practical utilization of the new electrical principles. They were the telegraph, electroplating, arc lighting, and finally the filament lamp. Of these, the first, as it demanded little current, led mainly to the improvement of batteries and receiving instruments, and thus largely to the development of electrical theory.

Electroplating, on the other hand, called for heavy currents and put a premium on the use of some forms of mechanically generated electricity. This led to the first applications of Faraday's principle, but one which employed only permanent magnets (Pixii's machine) and was thus weak and inefficient. Further, the demand of the electroplating industry could never be very extensive.

Arc light and dynamo

A far greater field was furnished by arc lighting, and the need for efficient generators was established. It was the discovery by Wilde (1833–1919) and Sir William Siemens (1823–83), in 1867, that the current from one machine could be used to

excite the field electromagnet of another that led to the first *dynamo*, the energy symbol of a new age (Fig. 13). With relatively cheap current available the emphasis turned to finding extensive uses for it, but here the most promising field was in domestic and shop lighting, for which the arc was too brilliant.

The solution to the problem of "subdivision of the electric light" was found in the incandescent lamp with a filament, first of carbon, then of metal, in its evacuated bulb. The technical problem of making a cheap and durable lamp was considerable, but it was not this that held up progress; incandescent lamps of sorts had been made in Russia by Lodygin (1847–1923) in 1872 and by Swan (1828–1914) in England a little later. For commercial production, the lamps required a greatly improved vacuum pumping system, but, given the incentive, that could have been achieved at any time in the century. The real difficulty was on the distribution and sales side. Edison's decisive contribution was the *power station* of 1881, with its network of mains serving electricity like gas or water.

The fifty years' delay between Faraday's discovery and Edison's application was thus due to no scientific or technical lag, but to essentially economic and social causes.[5.3] No means were available in the mid-nineteenth century for an organized exploitation of a scientific idea up to the stage at which it could pay its way. Once that stage was reached there was no holding it. Electric light and power had arrived; they were to expand in the next century at a rate far greater than that of steam.

The role of electricity in power distribution for transport, machine driving, heat, and light, as well as its use in the telegraph and telephone, all depended on an elaboration of the original electromagnetic experiments of Oersted and Faraday, reduced to a mathematical form by a generation of theoretical physicists, culminating in Maxwell. No radically new physical idea had, in fact, been added since 1831. The electrical industry of the nineteenth, and also of the twentieth century, apart from electronic applications, was an ideal example of a purely scientific industry depending on skill and ingenuity in using a limited set of principles for the solution of an ever-increasing range of practical applications.

The story of electricity and magnetism provides the first example in history of the transformation of a purely scientific body of experiments and theories into a large-scale industry.

The electrical industry is necessarily scientific through and through. Nevertheless, we find here the most irrefutable example of how at one remove scientific research can turn into engineering practice. There was no need for the men who were going to rig up telegraph systems to have the same scientific calibre as the inventors of the telegraph. This gave rise to the profession of the telegraph engineers who were incorporated in a society in 1871, which in 1889 changed its name to the Institution of Electrical Engineers. Within fifty years electrical engineering had acquired a tradition and code of practice. Problems of design and production, of economy in working and ease of repair had been superimposed on the basic scientific principles of electromagnetic induction. The wheel was in the end to come full circle, and the new profession was for a short time to furnish the livelihood of two young men who were to revolutionize physics, Albert Einstein and P. A. M. Dirac.

The electric discharge and the new physics

The practical triumphs of electrical engineering were not, however, to be the most fruitful ultimate consequence of the pursuit of the sciences of electricity and magnetism. Nor were they to lie in the further pursuit of electromagnetic theory. It was from a totally different set of phenomena—the curious luminous glows that had intrigued the first electrical amateurs of the seventeenth century—that the great new advances were to come, leading, as we shall see in Chapter 10, to the discovery of X-rays, the electron, radioactivity, electronic valves, atomic theory, and ultimately to atomic fission. This branch was not an obviously promising one; the phenomena were capricious and almost impossible to reduce to quantitative terms, and no practical applications came to hand to focus interest and lead to intensive research. It was accordingly pursued in a desultory way, and the exciting results which it could produce had to wait till the end of the century to be discovered.

9.4—*CHEMISTRY*

The central feature of science in the eighteenth and nineteenth centuries was the rise, indeed the establishment, of chemistry as a rational discipline of thought and practice. In the practical sense the science of chemistry was as old as, or older than, any other science; but as already explained (pp. 50, 160, 202)

it was not, and could not become, a logical science until very late, since the science of earlier times lacked the essential prerequisites. It was necessary first to wait for the accumulation of a far larger body of experience of the properties and transformations of a greater variety of substances than was available in ancient or Renaissance times. The rapid development of a widespread mining and chemical industry of a non-scientific and essentially technical character was a necessary precondition for the building up of any effective chemical theory. But it also needed some comprehensive ideas which would weld together these diverse experiments and make out of them a coherent picture which could be grasped and used to lead to further discoveries.

The end of alchemy

One preliminary requirement for any rational view of chemistry was the removal of the magical beliefs, drawn from classical and even earlier times, which still cluttered up the work of the practical chemist. Of these the most pernicious and difficult to eradicate were the astrological and mystical aspects of alchemy and its preoccupation with the then futile problem of making gold. The first attempt in the seventeenth century to make chemistry rational must, as we have seen (p. 331), be written off as a failure, though with the work of Boyle, Hooke, and Mayow it came very near to success. The corpuscular philosophy, with its over-rigid mathematical–mechanical models, could not, in fact, be applied to chemistry until its qualitative features had first been more thoroughly elucidated.

The search for chemical principles

The line of advance in chemistry was to be, for most of the eighteenth century, a quite different one. Instead of attempting to apply to chemistry rational principles based on mechanical models which could not cope with the enormous diversity of chemical facts, knowledge was to advance by a progressive rationalization of originally magical and animistic ideas. These, though at the outset inevitably vague, had an elasticity which enabled practical chemists to comprehend and set in order in a few verbal generalities all their multifarious operations. Only when this had been done was it possible to apply significantly the physical tests of measurement and calculation.

The great advance of the eighteenth century was to narrow down chemical problems to one central one, the problem of *combustion*—the operations of the spirit of fire (p. 203). The question was: What happened to combustible materials when they burnt in air? The obvious answer was that they disappeared in flame and smoke and left ash. This picture, however, was all very well for wood and oil, but was not easy to extend to other substances like metals which mortified or rusted in air. Had all these anything in common and what was the function of the air?

Some answers to these questions had already been provided in the seventeenth century. Jean Rey in 1630[4.83] and Mayow in 1674 [4.68] had established the cardinal facts that metals gained weight on heating in air, and that the air itself contained something of a " nitro aerial spirit " which was concerned in maintaining both fire and the breath of life. But these were isolated forerunners, unable to influence the general stream of chemical thought (p. 331).

The doctrine of phlogiston

Indeed this stream was flowing strongly in the opposite direction, towards the view that all combustibles contained a substance that they lost on burning. This was essentially the sulphur of the Arabs and Paracelsans, but it was given a new lease of life by Becher (1635–82) and his disciple Stahl (1660–1734) by christening it *phlogiston*, the principle of phlox or flame, though the phlogiston theory was only generally accepted by the mid-eighteenth century. Bodies containing much phlogiston burnt well; bodies that would not burn were de-phlogisticated. A body with much phlogiston, like coal, could transfer it to a body that had lost it, like iron ore, and by infecting it with phlogiston turn it into shining metallic iron. Even from the start objections were raised to this theory. It was pointed out that phlogiston was not a substance. It was essentially the opposite of a substance; it had no mass. But as we have already seen (p. 432) there was nothing strange in the idea of an imponderable fluid—electricity, magnetism, and heat, all of undoubted reality, were also of that nature. Even when it was established that some bodies actually grew heavier on losing phlogiston, this was put down either to a secondary accretion from the air or to the idea that phlogiston had natural levity.

We are apt, looking at it from the point of view of its immedi-

ate successor—the theory of combustion as oxidation—to treat the phlogiston theory as absurd; in fact it was an extremely valuable theory and it co-ordinated a large number of different phenomena in chemistry. It proved a good working basis for the best chemists of the mid-eighteenth century, and was firmly adhered to till the end by many of them, including the man whose experiments were to destroy it, Joseph Priestley (p. 375).

The logic of phlogiston

The central concept on which it turned was the universality of the antithetical processes of *phlogistication–dephlogistication.* Thus it brought together processes that were alike, and separated those that were unlike. As its opponents saw it, dephlogistication was not the removal of a metaphysical substance, phlogiston: it was the addition of a material substance, oxygen—*oxidation*; while phlogistication was its removal—*reduction.* It was necessary for the progress of chemistry that the balance should be the test. We can now in the twentieth century afford to reverse this idea again and return to phlogiston as a material, although a very light one; in modern parlance it could be spoken of as electrons. Those substances that have an excess of easily removable electrons, like hydrogen, metals, or coal, are those which were thought to be rich in phlogiston; those in which there is an exact balance of electrons, like salts and oxides, are dephlogisticated; while those that eagerly absorb electrons, like oxygen, would appear as highly dephlogisticated. The failure of the phlogiston theory was not on account of its internal illogicality, but because as it stood it could never be squared with the material facts. It needed to be turned upside down, phlogistication becoming de-oxidation, and dephlogistication, oxidation. The impetus for this inversion was to come not from traditional chemistry, but from another quarter—the study of gases.

The pneumatic revolution: wild untameable spirits: van Helmont

By the middle of the eighteenth century distillation was no longer any kind of novelty, and interest shifted to those products of chemical action that could not be recovered in the condenser, the "wild untameable spirits" of van Helmont (p. 303). Such spirits, ghosts, or gases (*chaoses*), as he called them, were well known in practice, particularly to miners, and

were beginning to attract the attention of scientists; they were the treacherous fire-damps and "inflammable airs" of mines and marshes that could be collected in bladders and burnt. There was as well the deadly *mofette* of caves, the "afterdamp" that followed explosions in mines, which was also to be found in brewers' vats and asphyxiated the workmen who occasionally fell into them.

Hales and the handling of gases

It was from the study of these *gases* that the clue to the explanation of chemistry was to be found. The Rev Stephen Hales (1677–1761) in his *Vegetable Staticks* had already, early in the century, shown how to collect gases over water and to measure their volume. Later Priestley and Cavendish collected them even more effectively over mercury. The next need was to recognize that these gases were not just air, but that there were *qualitative* differences between them. It was then necessary only to bring to bear on gases of different kinds the same quantitative treatment that Boyle had applied to the transformation of bodies.

The test of balance: the conservation of matter

The essential advance was that of extending the idea of weighing chemicals undergoing change to *all* the products of change and not, as in the old assaying, confining interest only to the weight of the original ore. As long as gases entering or leaving the reaction were not weighed or measured, it was clearly impossible to make the books of chemistry balance. That they should do so was first clearly enunciated by Lomonosov (p. 362) in 1774 as the principle of the conservation of matter, but his work was overlooked and it was left for Lavoisier to establish it as a fundamental principle in 1785, curiously enough from a study of the processes of fermentation.

Joseph Black: fixed air

The first step in the new quantitative pneumatic chemistry was taken by Joseph Black, a Scottish doctor who had his interest roused by Dr Cullen's first chemical lectures in Glasgow. Black wrote his MD thesis in 1754 on "Experiments upon Magnesia Alba, Quicklime, and other Alkaline Substances" in the search for a new and mild remedy for the stone, the most prevalent ailment of the heavy drinkers of the eighteenth

century. The House of Commons had voted an award of £5,000 to Joanna Stephens for revealing such a remedy, which was found to consist of calcined snail shells mixed with honey.

Black distinguished and weighed, as loss, the gas given off by carbonates such as limestone or magnesia when heated. He called it " fixed air " because he could absorb it in lime water and thus reconstitute the original carbonate, with an identical gain in weight. In this way he showed that a gas could be an integral part of a solid body, that it was strictly material and had nothing mystic left about it.

Joseph Priestley and the discovery of oxygen

The next important advance was due to Joseph Priestley (p. 375). It was in the course of writing a history of electricity, at Franklin's suggestion, that Priestley made certain experiments on electric discharges in air that led him out of the field of physics into that of chemistry. It is characteristic of these early days that the real advances in chemistry were not made by chemists. Chemists knew too much, they had theories that explained everything; it was for the physicists, who knew nothing, to provide fool or common-sense explanations.

Priestley had seized the notion that there was not only one kind of air. He played with as many gases as he could find and made many others. His first success was the preparation of *soda water* containing fixed air in solution. For this he was awarded the highest honour of the Royal Society—the Copley Medal. Though it disappointed the early hope that it would prove a cure for scurvy, the curse of long ocean voyages, it remained on its own merits, the first new commercial product of pneumatic chemistry.

One gas, which he made by heating red oxide of mercury (*mercurius calcinatus per se*), he chose to call " dephlogisticated air " because it had a greater affinity for phlogiston than ordinary air, that is, things burnt better in it. This was what we now call *oxygen*, and its discovery in 1774 was the culminating point of what may properly be called the pneumatic revolution of chemistry. Scheele in Sweden had also prepared oxygen at about the same time. He was a far better chemist than Priestley, but his interests lay rather in analysis than in the theoretical problems of chemistry, and so his discovery of oxygen did not contribute as much as it should have done to the solution of central problems. Priestley showed

that in burning and in breathing alike it was the dephlogisticated air (our oxygen) that was used up. He also showed that in sunlight green plants actually produced oxygen from the fixed air, or carbon dioxide, that they absorbed. He had thus solved in principle the essential problem of the carbon cycle: from the atmosphere through plants and animals and back to the atmosphere again. But he did not fully understand the significance of the range of his own discoveries, and it fell to Lavoisier, with his far more logical and well ordered mind, to make up this deficiency.

The overthrow of the phlogiston theory

Like Priestley, Lavoisier came to chemistry through physics (p. 378). Unlike Priestley, however, he did not spread himself in extensive qualitative experiments, but set himself limited and definite tasks of investigating the mechanism of combustion in air, which he saw was crucial to chemical theory. His work was precise, ordered, and *quantitative* throughout. In 1773, already conscious of the importance of the new pneumatic chemistry, and particularly of the fixing of air as a material fact, he formed the project of using it " to bring about a revolution in physics and chemistry." Later, hearing of Priestley's discovery of oxygen, he realized its significance at once, and was able to show that it alone was responsible for combustion, which was neither more nor less than the adding of oxygen, originally *le principe oxygine*, the acid-producer—a word he coined for the purpose. This ran absolutely counter to the phlogiston theory, but he did not hesitate a moment in attacking it, reversing all its arguments and putting it, as Marx did with Hegel, on its feet again (p. 762).[5.52]

The chemical elements

Lavoisier showed that the whole of the previously chaotic phenomena of chemistry could be ordered in a law of combination of elements old and new. To the established list of elements, in the sense of Boyle, not of Aristotle (p. 332)—carbon, sulphur, phosphorus, and all the metals—he added his new oxygen which together with *hydrogen* went to make up the old element water, as well as the other constituent of the air, the lifeless azote or, as we call it, *nitrogen*. According to this new system, chemical compounds were largely of three categories; those of oxygen and a non-metal, which were *acid*;

those of oxygen and metals, which were *bases*; and the combination of acids and bases, *salts*. Lavoisier made a clean sweep of all the old time-hallowed chemical nomenclature based on methods of preparation or fancied resemblances: oil of tartar per deliquum, sugar of lead, and so on, and introduced instead the terms we now use—potassium carbonate, lead acetate, etc. This step in itself marked the extension to chemistry of the same rationalizing process that had been applied to physics in the early seventeenth century, and also drew on the simplified nomenclature Linnæus had introduced in his botanical classification (p. 463).

Lavoisier himself, however, carried the same process one step further; making use of the rapidly accumulating data on the *quantities* in which various solid substances combined, he extended this to cover the newly found gases, and, thanks to his law of conservation of mass, reduced chemistry to accountancy into which only elements entered. Thus at one stroke he converted chemistry from a set of independent recipes, which had to be known one by one, to a general theory from which it was possible not only to explain the previous phenomena, but also to predict new ones in a quantitative way. Lavoisier was more a legislator for chemistry than a systematic chemist; he seized on essential points, and left to others, such as Berthollet (1748–1821) and Richter (1762–1807), the task of examining the nature of chemical affinity or the precise proportions in which chemical substances actually combine.

The primacy of chemistry

Lavoisier's success in effecting a revolution in chemistry aroused immense enthusiasm. Revolution was in the air, and the new chemistry, now so closely linked to physics, soon attracted to itself some of the most intelligent minds of the time, and helped to secure for France a predominant place in the world of science for nearly half a century.

The interest in chemistry was reflected in industry, and in turn industry supplied chemistry with new substances and new problems. The study of the glass-colouring mineral, manganese, by Scheele had led to the discovery of *chlorine* in 1774. Berthollet in 1784 found its use in bleaching, and McGregor, inspired by his son-in-law Watt, first used it on a large scale in the growing linen industry of Glasgow.[5.4] The other main

industrial chemical advances were Roebuck's manufacture of sulphuric acid (1746), which served to replace skim milk sours in bleaching, and soda manufacture from salt instead of expensive kelp and barilla,[5.4] according to the processes of Keir (1735–1820) in 1769 and Leblanc (1742–1806) in 1790. Though Leblanc himself was left to die in poverty, his process was perfected by direct orders of Napoleon, and its success made France independent of supplies of soda from countries controlled by England. All these processes were essential adjuncts to the enormous increase of textile output that was the main growing point of the Industrial Revolution, and was outrunning the limited supplies of vegetable products. Even where, as in these cases, the processes arose from traditional or phlogiston theory, their success and the anticipation of further successes to come stimulated the study of chemistry, and led to the ready adoption of the new rational doctrines.

The chemistry of eating and breathing

Lavoisier's other contribution to science was to make quantitative Priestley's qualitative pictures of the chemical nature of the process of life, and he thus became the father of quantitative physiology. By a set of admirably designed and executed experiments he was able to show that a living body behaved in exactly the same way as fire, burning up the materials in the food and liberating the resulting energy as heat. For the first time the general chemical balance sheet of organisms could be established, and the real significance of the mechanisms of breathing and of the circulation of the blood, discovered by Harvey nearly 200 years before, was revealed.

Dalton : the atomic theory

The next crucial step in the understanding of chemistry was taken twenty years later by John Dalton (1766–1844), a Quaker weaver and school teacher of Manchester. He, like Priestley and Lavoisier, was not primarily a chemist but a physicist and meteorologist. He was interested in gases as elastic fluids, and tried to explain their properties on Newtonian principles by the mutual repulsions of the *atoms*. This led him to consider the possible proportions of atoms in different kinds of gases, and thus to see how to explain the laws of combination of elements in multiples of definite weights, which had gradually emerged from the analyses of the new gases such as nitrous

oxide, nitric oxide, and nitrogen peroxide, which we write, following Dalton, N_2O, NO, and NO_2. These followed simply from the assumption that all chemical compounds were made up atom by atom—the atoms of different kinds arranging themselves in pairs, threes, or fours.

Crystallography : Haüy

Other regularities, those occurring in crystals, were also about this time pointing to an atomic explanation. Steno in the seventeenth century had shown the invariability of the *angles* between the faces of a crystal. Huygens had seen that this implied that the crystal must be built of identical molecules piled together like shot, or, as Newton called it, "in rank and file." It was, however, left to a retiring French abbé, Haüy, in 1800, to generalize these observations and to show the ways in which these molecules could be associated in different kinds of crystal. It was later found by Mitscherlich (1794–1863) that similar compounds had nearly identical crystal forms, so that the new science of crystallography could become a useful adjunct to chemistry.

Electrolysis : Humphry Davy and Faraday

Another adjunct was to be found in electricity. The new electric current (p. 436) was found to decompose not only water but also salts. Davy in 1807 prepared the new metals, sodium, potassium, and calcium, from the previously undecomposed alkalis and earths, thus completing Lavoisier's scheme and dividing all elements into metals and non-metals. It was found that metallic atoms were charged positively and non-metallic negatively. Faraday indeed showed that the rate of transport of atoms in solutions was proportional to their combining weights, and this, of course, leads logically to the concept of a single common atom of electricity—what we now know as the electron. But that final step was to wait for another seventy years, so strong was the prejudice against imputing atomicity to a fluid.

Inorganic and mineral chemistry : Berzelius

The electrical theory furnished a simple explanation of how salts were formed by the mutual neutralization of positive and negative charges, and this led, particularly in the hands of the great Swedish chemist Berzelius (1779–1848), to the

determination of the constitution of most kinds of inorganic compounds and minerals in the first half of the nineteenth century.

The new non-traditional chemical industry which had started in the eighteenth century now grew rapidly under the double impetus of the new knowledge and the vastly increased demands of other industries, especially the dominant textile industry. It was still, however, undertaken in establishments small enough to permit close working contact between scientists and manufacturers, even when these were not the same person. This new industry provided the link between the mineralogical chemist, interested principally in assays of ore, and the druggist with his concern with vegetable and animal products.[5.3]

Organic chemistry: Dumas and von Liebig

Thus for the first time a firm and permanent economic base was provided for chemistry, far larger and better supplied than the pharmacist's shop of the past, and from this base it was possible to build out into the more difficult realms of organic chemistry. Nevertheless, in spite of the genius and ability of the workers in this field, this proved to be a very slow process. Actually the extraction and purification of most simple organic substances such as oils, sugars, and vegetable acids were relatively easily achieved; so was their analysis in terms of the newly known elements, carbon, nitrogen, oxygen, and hydrogen. But the figures obtained by themselves did not tell much —they needed a new kind of interpretation.

This was the work of the new chemists, first in France with Gay Lussac (1778–1850), Laurent (1808–53), Gerhardt (1816–1856), and Dumas (1800–84); then in Germany with von Liebig and Wöhler (1800–82). It was Liebig more than any other who restored the primacy of Germany in chemistry after nearly seventy years of French predominance. His laboratory at Giessen was to be the model for the modern chemical teaching and research laboratory. Gradually, from the study of simpler substances—fats, fatty acids, and alcohols—ideas of *structure* began to emerge. As a consequence of a fiasco at a ball where new patent candles bleached with chlorine emitted a frightful stench, Dumas, who was asked to investigate, found that chlorine could be substituted for hydrogen and was led to a general theory of *substitution*. From that followed a theory of *types* of molecules, like alcohols, with some part in common,

and then of *radicles*, the detached parts themselves like methyl or benzoyl, which could play the part of atoms.

Such structure could, of course, be merely additive, though already in 1823 von Liebig had found a case of *isomerism*—two substances with the same composition but with different chemical properties. This pointed clearly to some difference of arrangement inside the molecule, but such ideas were firmly resisted, mostly for metaphysical and philosophic reasons. The hypothesis of atoms was not acceptable to a large number of scientists. It seemed to some to go far beyond what experience showed; to others to smack of radical deism. There was also a strong reluctance to believe that substances formed by living beings could be made in the laboratory.

Avogadro's law

Organic chemistry might have remained a classified collection of identified substances with mass formulæ, and of reactions for turning some kinds into others, had it not been for two impacts from the physical sciences. The first was the recognition of a law originally put forward as early as 1811 by Avogadro (1776–1856), but not generally recognized until restated by Canizzaro (1826–1910) in 1860. This law states that equal volumes of all gases under the same conditions contain the same number of molecules, thus enabling the correct number of each kind of atom in a molecule to be determined.

Asymmetrical molecules : Pasteur

The second discovery was that of the separation of racemic acid into two components, one ordinary tartaric acid, the other chemically identical but physically different. This discovery, which was to prove of central importance for the science of the nineteenth century, was made in 1848 by Pasteur, then a young man of twenty-five.[5.3] He showed that whereas molecules made by ordinary laboratory processes did not rotate the plane of polarized light, those naturally produced did so. The former consist of two kinds of molecules of opposite configurations, like right and left hands, in equal numbers; the latter contain only one kind of molecule.

From this critical observation two very different consequences followed. The first was that molecules possessed a shape in three-dimensional space, in other words it was possible

to picture them as solid models. The second was that Nature must set about making molecules in a different way from the chemists of that time, and further that there must exist in organisms definite chemical structures which were right-handed, let us say, and not left-handed. Pasteur himself followed the line given by the second clue, which set him among the founders of modern biochemistry and later of bacteriology.

Kekulé and the benzene ring: Valency

It was along the other branch that lay the future of organic chemistry, although it was still very slow to evolve. The idea that molecules could be pictured as patterns of atoms in space had been evolved logically by the brilliant German chemist Kekulé (1829–96), who in 1865 conceived the idea as he sat on top of a London bus, that the benzene molecule C_6H_6 contained a ring of six carbon atoms:

From then on it was no longer sufficient to give the numbers of atoms in the molecule of a substance, a mere accountant's description; but to indicate by some kind of plan—an architect's conception—how they were arranged by means of a *structural* formula. Thus he added a decisive proof to the idea that was gradually dawning, that different kinds of atoms were characterized by the number of links that they could make with other atoms. Hydrogen had one, oxygen had two, nitrogen had three, carbon had four of these links or *valencies*.

van't Hoff and Le Bel: spatial chemistry

It was not until twelve years later that simultaneously van't Hoff (1852–1911) and Le Bel (1847–1930) realized that the four carbon valencies could not lie in a plane but must stick out in space, and thus made it possible to explain the two different, right- and left-handed, configurations that Pasteur had discovered twenty-five years earlier. From now on three-dimensional structural organic chemistry became a branch of applied geometry, and it was possible both to analyse and to synthesize very complicated compounds.

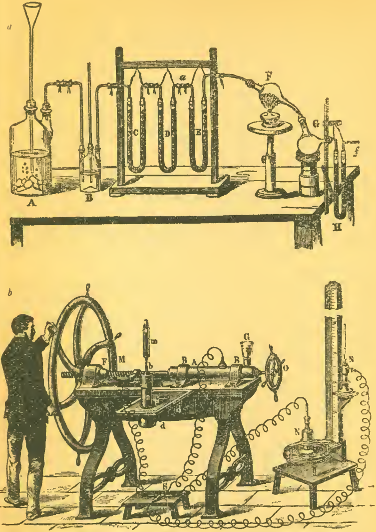


FIG. 14.—NINETEENTH-CENTURY CHEMISTRY AND PHYSICS

(*a*) Analysis of the composition of water by passing hydrogen over copper oxide by Berzelius and Dulong.

(*b*) The liquefaction of oxygen by Cailletet, 1877. The gas is compressed by the screw-pump and liquefies in the cooled tube when the pressure is released.
From Graham's *Elements of Chemistry*, 1850.

Synthetic dyes and the German chemical industry

Even before this, however, organic chemistry had established itself in a practical way. Almost by accident Perkin (1838–1907), seeking to make a substitute for quinine, had discovered in 1856 the first artificial aniline dye, magenta, finding at the same time an outlet for the products of coal tar from the gas industry. Chemistry in England, however, was still the pursuit of a few amateurs and even fewer academic university departments, while the chemical industry was proud of being "practical." Perkin's discovery, neglected in Britain, was taken up immediately by the more scientifically-minded directors of the new German industry, and the rapid profits accruing from synthetic dyes were ploughed in to create an enormous and dominating German chemical industry. This, though at first ancillary to the textile industry, was, through its capacity for the production of nitric acid for use in the new explosives, to provide the sinews for both the First and the Second World Wars.

The chemist, particularly the chemist of the latter part of the nineteenth century, was effectively a new kind of scientist, one much more closely tied up with industry than the physical scientist of earlier times. The tendency to identify science with industrial interests which this brought about was one of the major factors that led to the general toning down of scientific controversy, especially of radical scientific attitudes, at the end of the nineteenth century.

From the purely scientific point of view, however, the establishment of molecular constitution by the methods of organic chemistry is one of the greatest logical achievements of the human mind. The decisive steps were made by very few men, but they were followed by a great crowd of chemists who, using the logic of chemical transformation, were able to imagine the most complicated patterns of atoms in space and actually to make substances having those patterns, thus proving by *synthesis* what they had previously established by *analysis*. In this way organic chemistry grew up as a discipline almost independent of physics, having its own rules and its own way of working.

Physical chemistry

This, however, did not apply to the whole of chemistry, especially on the inorganic side, where interest began to shift

from the actual composition of bodies to their modes of reaction with each other, to the influence of heat, to such questions as solution, crystallization, and electrolysis. From these interests there grew up a new branch of chemistry ultimately to become a new subject, *physical chemistry*. This was the first hybrid science, one which was to be the prototype of other " bridge " sciences that in the twentieth century were to link all science into one effective unity. The value of physical chemistry began to make itself felt when attempts were made to exploit industrially the new deposits of mineral salts, particularly the great salt deposits of Stassfurt, which could not be disentangled into their components economically without these methods. It was also the basis of whole new chemical industries such as the Solvay ammonia soda process, which replaced the Leblanc process for the manufacture of soda, and the catalytic processes on which the manufacture of sulphuric acid and of ammonia were based. These were the processes which were to be the main basis of the greatest chemical monopoly concern in Britain.

Early biochemistry

The new organic chemistry had another essential part to play in the history of science—it was to lead to a fuller understanding of biological processes. In fact, the beginning of any deeper understanding than the microscope could provide was totally impossible without a knowledge of the laws of combination and the types of structure actually to be met with in biological systems. The nineteenth-century development of organic chemistry had to precede logically any attempt to formulate a fundamental biology.

The main features of animal and plant metabolism as far as carbon, hydrogen, and oxygen were concerned—that is, as far as an animal can be treated as a heat-engine—had been established in the eighteenth century; but it took much of the nineteenth century to establish the equally important role of nitrogen. It was the work of von Liebig that showed what kind of food—nitrogen, phosphates, and salts—plants drew from the ground. The great *cycles* of transformation of the elements, such as that of nitrogen from plants through animals back into the soil, were traced out and even followed into the air with nitrogen-fixing organisms. This was still a far cry from understanding the functions of these inorganic substances in the organism. It is one thing to study the properties, mainly the

industrially useful properties, of materials derived from once-living sources; it is quite another to follow them in their transformations during metabolism. That is why organic chemistry took so long to be transformed into *biochemistry*. Nevertheless, as the century came to a close, chemical interest began to shift from the immediately profitable synthetic chemistry of the dyestuffs industry towards an understanding of the more detailed structure of organic substances of a natural kind. This is shown particularly in the great work of Emil Fischer (1852–1919) on the sugars and on the matter of life—the proteins—which he was able to show consisted of chains of much simpler compounds, amino acids. There also, as a by-product of dyestuff chemistry, was laid the beginning of a new chemical pharmacology in the provision of remedies, such as Ehrlich's (1854–1915) salvarsan for syphilis and Bayer 206 for sleeping sickness, which were to foreshadow the triumphs of chemotherapy of the next century (pp. 641 f.).

9.5—*BIOLOGY*

With the development of physical science throughout the eighteenth and nineteenth centuries, and interacting with it at many points as we shall show, came a renewed approach to a scientific understanding of living things. The roots of this lie much farther back in classical times with the natural history of Aristotle and the physiology of Galen. After a long interval of purely formal and moral interest in Nature, as symbolized in the bestiaries and herbals, interest revived in the increasing pictorial naturalism of the late Middle Ages and the Renaissance, spiced as it was by the wonder and anticipated riches of the New World. Anatomy and physiology were, as we have seen, revolutionized in the sixteenth and seventeenth centuries, and another new world of the very small was opened up by the first microscopists (p. 328).

The lively interest, however, of the seventeenth-century pioneers in biology, as in physics, turned, towards its end, on one side to a dilettante amusement in the curiosities of natural history, and on the other to the service of a pedantic medicine which included a study of botany and zoology primarily as sources of drugs. This period of discursive observation was, however, to be a very necessary stage in the history of biology—a science incomparably richer in detail than physics or even

chemistry, and one consequently where almost innumerable facts had to be collected, examined, and arranged in order before any sense could be made out of them, a task which was to take over 200 years.

The main drives that determined the direction of biological interest, and with it of biological progress, in the eighteenth and nineteenth centuries, were first, those of geographical exploration, largely undertaken in the hope of finding and exploiting new natural products; secondly, the needs of an awakening medicine, with its emphasis on physiology and anatomy; thirdly, the needs and problems of the agricultural revolution which accompanied the transition from traditional subsistence farming to commercial farming for a market; and, lastly, the needs of vastly expanded industries, including those of textiles, food, and drink, largely dependent on animal and vegetable products and, by the very scale of their operation, unable any longer to rely on tradition. These interests all overlapped and interacted. The first two drives remained all the time, though exploration fell and medicine rose in relative importance. Scientific agriculture did not come in till the late eighteenth century, and industrial biology not till the middle of the nineteenth.

Compared with the interests in physical and chemical science, where, as we have seen, there were a limited number of problems set by the advance of industry itself, biology was pursued in a widely scattered and almost casual way. Less able to establish its advances by processes of practical utility, it was necessarily more easily influenced by currents of thought outside science, and particularly, over the whole of the period, by the great religious and anti-religious battles that in different forms convulsed both the eighteenth and nineteenth centuries across the great divide of the French Revolution.

The religious hoped to regain in the animate world the justification for divine governance that had been lost among the celestial spheres. The rationalists hoped, on the contrary, to expel the spirits from the universe by demonstrating the mechanical operation of matter in the phenomena of life, and to explode once and for all the naïve myths of Old Testament creation. Naturalists of both convictions diligently searched Nature to pile up more convincing proofs of what they were certain must be the only right view. Religious preconceptions had no longer the power to prevent research, but they did, at

least until the triumph of Darwinism, hold up its most obvious implications. Every inch of the way to the rational interpretation of the world of life had to be fought for, and the only consolation is that, perhaps for that very reason, if it took longer to establish, it was the better understood.

It is in biology, more than in physics, though less than in the social sciences, that men have embraced, often at the same time, the rival stupidities of the commonplace and the marvellous. On the one side everything in Nature is obviously natural—no explanation is needed as to why the grass grows or the lions roar. It is their nature to do so; they always have, and they always will. If from the evidence of fossils or from the tradition of a creation it is admitted on the contrary that the world as we know it must have once been different, it is far easier to believe that it began with a bang, or at most in seven days and from nothing at all, than to attempt to trace its rise step by step from something unfamiliar but not radically different from what we see today. Right up to 1859 the most practical and common-sense naturalist or geologist was quite ready to admit universal catastrophes, compared to which Noah's flood would be a minor incident, without any mental uneasiness.

In any case, from its very complexity, the great generalizations of biology could only be established on the base of a most extensive and intensive exploration of living things, and this was in the first place to be the task of the natural historians. In what follows we will first trace the development of natural history and its companion study, geology, to its culmination in the theory of organic evolution. For all its importance in the history of human ideas, this great theory was based merely on the external appearance and gross anatomy of living and fossil organisms and had few practical consequences. The other approach through the study of the internal constitution of organisms, large and small, begun by the use of the microscope and continued by the methods of chemistry, was much more searching. It was, towards the end of the nineteenth century, beginning to show its promise of practical utility in the curing of disease and the nourishing of crops.

Natural history and classification : Linnæus

The eighteenth was the great century of travellers, collectors, and classifiers. The idea of classification arose from the practi-

cal necessity of arranging plants in botanical gardens, collections in cabinets, and even more perhaps from the making and printing of catalogues. Very naturally, each collector and cataloguer had his own ideas as to how to arrange his material, and the result was a welter of confusion of names and arrangements.

It was only in the middle of the eighteenth century that an energetic and systematic young Swede, Carl Linnæus (1707–78), afterwards ennobled to von Linné, the son of a poor parson and almost self taught, took upon himself, at first single-handed, the task of classifying all animals, minerals, and particularly vegetables in the world. In botany, where his chief contribution lay, he had the genius to see that the great discovery of Camerarius (1665–1721), that flowers were the sexual organs of plants, was the key to their classification. Basing himself on the numbers of the hitherto neglected stamens and pistils, Linnæus divided the plants into classes and orders. For the finer divisions of genera and species he established the double-name nomenclature, *Primula farinosa,* which would provide enough actual words to enable every living thing to be distinguished.

The time was ripe for such an organization of knowledge, even if quite arbitrary—for at first it was little more. Linnæus travelled widely, collected copiously, and built up a systematic botanic garden at Uppsala. He soon attracted a band of devoted disciples who travelled all over the world to complete his classification, and found everywhere admirers and imitators. The Linnean Society of London was founded in 1788. On the basis of his simple system and his undoubted mastery of the material, Linnæus imposed his classification on the whole of the learned world. With later modifications it remains that of botany and zoology to this day. On the other hand, his classification of minerals, being based, inevitably for the time, on unscientific principles, was soon abandoned and gave way to the more rational system based on chemistry and crystallography.

Towards a natural system : Buffon

Armed with this system, the naturalists, in whatever part of the world they were, could work together knowing that if they got the name right they were talking about the same organism, and that thus they could contribute to building up a common

catalogue of organized beings, a process which is continuing to our day. The Linnean system was too rigid to start with; but it was possible, without substantially breaking it up, to alter it progressively till it became more and more a natural system: till species that resembled each other more than any others appeared together in the same genus, while the larger groups, genera and families, were divided from each other by more important differences.

The work of the systematists had immediate and lasting practical value. Scientifically, however, its establishment had a much more far-reaching consequence. It was impossible henceforth to contemplate the natural classification of living things without being forcibly reminded of their relationships, which were indeed implied by the very terms used, those of genera, or tribes and families. One of the first to sense this was George Louis de Buffon (1707–88). By his brilliance and affability he did more than any other man to popularize natural history both at the French Court and among the rising bourgeoisie, of which he was an ennobled member. In 1739 he was made keeper of the Jardin du Roi, now Jardin des Plantes, and turned it into what was, for the time, a great research institute, where many of the biologists and chemists of France received their inspiration and training (p. 378). Unlike Linnæus, who lacked any other knowledge than that of natural history, Buffon was originally a physicist and brought the rational ideas of the Newtonian synthesis into the field of biology; he was, however, possibly for the same reason, by no means as patient an observer or as diligent a classifier. He set the fashion in the literary presentation of science, and his daring ideas on the origin of the world, of plants, animals, and of man himself, endeared him to the *philosophes* and the makers of the French Revolution.

Buffon, in his monumental *Système de la Nature*, claimed that the relationship implied by the classification of animals and plants was a real one. In this he was supported by Erasmus Darwin (1731–1802), who has already been mentioned as a leading member of the Lunar Society. He was a successful doctor of Lichfield, a poet, a popularizer of science, and a speculative and daring theorizer in biology. His *Zoonomia* was an attempt to trace the origin of life from a primitive filament, which produced the great variety of observed living forms as a consequence of its different reactions to a variety of external in-

fluences. As he could not have had any knowledge of either the intimate structure of living matter or of the mechanism of its reactions, his ideas were necessarily speculative, and served more immediately to support the *naturphilosoph*-romantic school of Germany (p. 469) than to lead to any new observations and experiments. Still, what he dared to think others, with better grounds, could think after him.

If it had not been for the pietistic reaction against the French Revolution the idea that all species came from a common stock would have been freely accepted early in the nineteenth century. However, almost more than in the seventeenth century or in the time of the counter-Reformation, it was necessary in the early nineteenth century to uphold the literal truths of the Bible stories of the creation of the species, of animals and plants, on the appropriate days, so most naturalists for over fifty years put their blind eye to their microscopes and refused to think about the meaning of the system of Nature.

Early evolutionists : Lamarck

In spite of this, some continued to speculate, of whom the most original, Lamarck (1744–1829), botanist at the Jardin du Roi, boldly propounded the theory in 1809 [1.14] that the species of today were derived from those of previous times by an adaptation brought about by their desire to fit more closely with their environment. The giraffe, seeing leaves growing on a high tree, stretched his neck, and that stretching was inherited by his descendants. The idea seemed far-fetched and won little support, but meanwhile the evidence was accumulating, and not only from the study of living organisms, but now even more from that of fossils.

Speculative geology and creation

The study of geology came late into the category of sciences. It was pre-eminently a field science. The collector in his cabinet could do little but marvel at the odd productions of the earth. The miner, on the other hand, was so concerned with the ore and the indications of its presence in other rocks that he had usually neither the inclination, nor the learning, to formulate any general theories as to the structure and history of the earth. Yet speculation about the earth and its fossils grew steadily in

the eighteenth century with the general increase of interest in Nature. In fact, from even earlier times, the idea that the shells found in mountains implied the presence of sea had led to speculations about the antiquity of life, though in the past the whole matter had been easily smoothed over by putting it all down to Noah's flood. From voyages and astonishing accounts of foreign volcanoes and earthquakes another view began to be held: that the world was subject to continual cataclysms in which the crust was broken up by internal fire; and the controversies between the neptunists, or flood-believers, and the plutonists, or earthquake-believers, remained an unprofitable exercise throughout the latter part of the eighteenth century.

Hutton and common sense

The first radical break from speculative geology came from Hutton, an Edinburgh doctor, a close crony of Black's, and one of the great company of brilliant scientists and philosophers who had made their city the Athens of the North (p. 373). In his *Theory of the Earth* (1795) he put forward the idea, revolutionary in its common sense, that the phenomena of geology are the products of forces that we still see acting round us. From his walks in the country, from his experience as a practical farmer, he concluded that valleys were cut by rivers, and plains deposited out of the mud they brought down, which then hardened into rock. He also understood that the massive unstratified rocks of Arthur's Seat could not have been deposited from water, as the arch neptunist, Werner (1749–1817), maintained, but must have been formed from the solidified lava of an ancient volcano. These views were too rational to survive the reaction against the French Revolution, which brought in a school of geologists, often in holy orders, who were everywhere looking for vestiges of creation,[5.35] but Huttonian views never entirely disappeared.

The success of field geology came from the experience of cutting canals rather than from the intensive and highly localized craft knowledge of the miners. William Smith (1769–1839), the practical surveyor and canal-maker, realized from his work that throughout the whole of southern England the layers or strata of the earth lay over one another in one invariable series, and he spent most of his life plotting their outcrop in the first of geological maps.

Lyell's "Principles"

Catastrophic theories of how these strata came to be laid down became more and more difficult to maintain. They were quietly dropped when Lyell in his *Principles of Geology* [5.49] revived Hutton's doctrines of the operations of natural forces, and founded his *uniformitarian theory*, based on far more extensive observations. But if every stratum represented a deposit of a certain age, the distinctive fossils it contained must have belonged to animals living at that time, and these fossils corresponded to quite different forms of life, and even showed definite progressions. Reptiles, for instance, did not appear before the secondary, or mammals before the tertiary strata. Lyell, accepting as a logical necessity the fixity of species, could only deduce that a whole new fauna had been created at every geological age and had become extinct in its turn. Obviously all this must have taken a very, very long time, so that the Bible story of the Creation, quite apart from its miracles, became increasingly difficult to believe. Yet, in the atmosphere of reaction in the early nineteenth century, it was extremely daring to question it.

Charles Darwin and organic evolution

In fact, it was not until the evidence was altogether overwhelming, and there was in addition some plausible mechanism to explain how different kinds of animals could have descended from each other, that it was possible to break the spell of ancient religion. To provide for that mechanism in the form of natural selection was to be the work of Charles Darwin, the grandson of Erasmus Darwin. He was a typical by-product of mid-Victorian capitalism, a man of independent means who, after a formative voyage round the world in the *Beagle*,[5.23] could settle in his study and garden at Downe House and survey minutely and carefully aspects of animate Nature bearing on the problem of the origin of species.

Darwin had been particularly impressed by the species problem in his study of the distribution of rare species on isolated islands such as the Galapagos. It was very tempting to imagine that such species had come from ancestors on the mainland and had somehow grown different—but how and why? Might it have something to do with the conditions of their life which favoured some features more than others? He began to think that possibly the conditions of competition of human economic

life might also apply to the animal world. Indeed a fully elaborated theory built to justify capitalist exploitation was ready to his hand. Life, according to parson Malthus (p. 729), was a struggle in which the best survived, and wealth and position were the rewards of virtue in this struggle. Disease and war were the means by which a population was kept from becoming more numerous than the available food supplies could support. If the same were to happen in animal societies, thought Darwin, those that varied ever so little in the direction of being more fit for their environment would pass on that advantage to their descendants, and so, gradually, the species as we know them now would evolve. The hungry 'forties was a very suitable time to observe this phenomenon taking place.

Natural selection

Darwin, however, was a most cautious man and did not publish this idea. Instead he spent nearly twenty years building up the evidence for it. He drew it from all sides of natural history—from the record of the rocks, which showed the gradual elaboration of form in previous ages; from the distribution of animals and plants in the world; and finally from the study of the great breeding experiments that were going on in the nineteenth century, partly to improve stock and partly for fancy breeds of dogs or pigeons, which provided him with examples of changes as strange as any that occurred in evolution. Yet he might not have published his theory at all even then if another and much younger traveller, Alfred Russel Wallace (1823–1913), had not independently come to the idea of evolution of species through his study of the distribution of animals in the East Indies.

The " Origin of Species " and the evolution controversy

The explosion that followed the publication of the *Origin of Species* showed how prudent the retiring Darwin had been in holding back his ideas. Even in the relatively advanced 'sixties they were to create a prolonged and bitter controversy. This, however, was to turn on questions of a rather theological or political than of a purely scientific nature (p. 484). In biological science it produced an enormous effect of liberation. It provided a unifying principle for the whole living world.

However, the effect of Darwinism on science was not an altogether happy one. It certainly did raise a great interest in

biology and drew many people into it. But at the same time the emphasis that Darwin's theory gave to the simple tracing of evolutionary relationships between organisms and the building of elaborate family trees distracted naturalists from the study of the actual lives and of the inner workings of animals and plants. For this no one could blame Darwin himself, who was, as his detailed researches on such varied topics as earthworms, carnivorous plants, and the expression of the emotions show, one of the pioneers of experimental biology.[5,20-22]

Naturphilosophie

The sequence of the species controversy has been followed down to the end of the nineteenth century. It is now necessary to go back to the beginning of the century to pick up another thread to the understanding of living things from the study of their structure. Here again much of the initial impulse came from natural history, but more from the aspect of anatomy and physiology with its close relation to medicine.

It was especially in biology that the mystical trend in science —Neoplatonic, Lullian, Paracelsan—found its last serious expression in the German *Naturphilosophie* of the early nineteenth century. Inspired by philosophers like Herder and Schelling and by poets like Goethe, there came the search for the Absolute Idea or the Divine Plan of Nature, which was also incomprehensibly bound up with the regeneration of the German people and the destruction of abominable French mathematical materialism.[1,14] Nevertheless, the search for the Archetypes meant a comparative study of the structure or *morphology* (the word is Goethe's) of animals and plants, which was to continue long after the ideas that had given rise to it had evaporated. Lorenz Oken, already mentioned as a refounder of German science, was one of the finest representatives of this school, and was responsible for the recognition of the common features of the structure of the main groups—phyla—of organisms living and extinct (p. 392).

The microscope: tissues and cells

Besides this naturalistic approach there was another from medicine. Though the amalgam of classical Galenical medicine with its Arab commentaries still dominated medical practice, the old theories of medicine based on the humours could not stand

in the face of the advance of chemical and biological science. Yet even as late as the beginning of the nineteenth century there could be nothing effective to put in their place. The result was an era of wild speculation and system-building in which inspired quacks, like Mesmer with his animal magnetism, and over-confident anatomists, like Gall with his phrenology, gained a wide following.

At the same time, the renewed interest in anatomy and physiology was to lead to the greatest advances since the Renaissance in the understanding of the body in health and disease. Bichât (1771–1802), in his short life, virtually re-founded *pathology*, and by the careful study of the structure of the different organs distinguished the tissues—nervous, arterial, venous, muscular, fibrous, glandular, epidermal—that were common to many of them. This study was followed by others in which the new achromatic microscopes of Amici (1827) enabled a far greater insight to be obtained into the fine structure of tissues, *histology*, than had been possible to the pioneers of the seventeenth century. This revealed that the tissues in turn were composed of cells—square cells for the liver, long cells for the muscles, enormously elongated cells for the nerves.

The cell theory

The whole body, as Schlieden (1804–81) and Schwann (1810–82) pointed out in 1839, could be treated as a colony of *cells*, and, what is more, all had arisen from one, or rather, two cells; the cell of the egg and the cell of the sperm. The actual growth of the organism from the fertilized egg-cell had been followed out by von Baer (1792–1876) at about the same time. The new science of *embryology*, which he virtually founded, also brought out the kinship of different animals in each great group or phylum such as the vertebrates. The cell theory made intelligible the growth of the individual, just as natural selection was to make intelligible the development of the species; and both seemed to be following a parallel track of evolution. The use of the microscope in all fields of biology began to reveal unsuspected complexities, but in the early stages they had very little effect on actual practice. It was only when the simplest kind of animals and plants, the fungi [4.47] and the simpler single-celled protozoa and bacteria, came to be studied that some understanding of the life and

functions of cells was reached, and with it the possibility of the control of living organisms.

Fermentation

As often happens in the history of science, this achievement was to come from right outside biology, from the study of agricultural pests and of industrial chemistry. From before the dawn of civilization man had made use of processes generally known as fermentation when the result was pleasant, or as putrefaction when it was not. By careful practice and exact following of rules they had even managed to secure a definite and reproducible control of certain limited sets of processes—the brewing of beer, the maturing of cheese, or the tanning of skins; but, like all technically achieved processes, it was extremely difficult and very dangerous to change them, and the enormous expansion of demand that was created by the new populations of the early nineteenth century made not only for expansion in consumption but also for numerous disasters.

Pasteur and bacteriology

It was in the growing industrial town of Lille in 1855 that the young professor of chemistry, Pasteur, first came into contact with the activities of living ferments. The beer and the vinegar, usually good, would sometimes unaccountably go bad, and Pasteur, finding no chemical explanation, looked at them through the microscope. He found that when normal fermentation went on there were the little round cells of yeast, already studied in 1839 by Caignard de la Tour (1777–1859), but abnormal fermentations were characterized by different organisms, what he called the vibrios, because they kept on dancing continually in his field of view.

Now Pasteur had already, as we have seen (p. 455), been concerned with the chemical activity of living things in producing asymmetric molecules. His experiments with moulds had convinced him that the processes of fermentation themselves must be due to living organisms and not to any inert chemical reactions. As a chemist he studied not only the appearance of the micro-organisms but also their chemical performance. He investigated whether they could live in or out of the air, and as a result was able to devise ingenious but practical ways, including the process now known as pasteurization, of preventing them interfering with the successful production of beer or vinegar.

It was his knowledge of the living organisms in fermentation that spurred Pasteur on in his vigorous denial of the possibility of spontaneous generation of life and which led to his famous controversy with Pouchet (1800–72). There he showed that by excluding the invisible *microbes* of the air, animal and vegetable substances could be kept indefinitely without putrefying. He thus convinced the learned world of the facts which the chef, Appert,[5.12] as far back as 1810, had made use of in his method of preserving foods by boiling them and sealing them in glass vessels, which was later to be the basis of the great canning industry. It had, however, been objected that Appert's bottles contained no oxygen, which was claimed as the cause of putrefaction. Pasteur had to show that the filtering of air was equally effective in preventing putrefaction.

Pasteur's preoccupation with the organic side of fermentation also brought him into opposition to von Liebig's view that it was due to a specific chemical ferment, and his success pushed this into the background. It was only in 1897 that E. Buchner (1860–1917), almost by accident, isolated such a ferment from ground yeast and inaugurated the study of *enzymes*. Thus in the end both von Liebig and Pasteur were proved right. Fermentation is brought about by a ferment, but that ferment can only be elaborated by a living organism (p. 616).[5.3]

The silkworm disease and the germ theory

In 1865 Pasteur was called to a more difficult task. The new industries of France depended very largely on the supply of silk, and this was threatened with extinction by a mysterious disease of the silkworms. Pasteur was sent to deal with it. At the time he was so little a naturalist that he did not even know what a silkworm was or that an ugly caterpillar later turned into a beautiful moth. Nevertheless, after a season's intense research he found that the disease was due to a kind of organism that actually lived and grew inside the caterpillar itself. This provided the clue to wiping out the disease.

From then on he came to think more and more that the diseases of larger organisms, of animals and of men, were due to similar causes, to the minute germs of disease. This was not a new idea. In effect, it was as old as disease itself, and the phenomena of infection and epidemics bear witness to it. Jenner, indeed, had long before taken the first official practical step to control smallpox by *vaccination*, which presupposed the

presence of an active *virus* of disease in a milder form in contrast to the drastic *inoculation* with smallpox itself which had been practised for centuries. But these *germs* of disease could never be recognized, and the medical profession, into whose Aristotelian or even Hippocratic theories they did not at all fit, refused to admit their existence. Yet they had been seen years before by Leeuwenhoek by means of his simple but excellent microscopes. But there seemed to him no obvious connection between the minute creatures that he saw and the diseases that afflicted animals and men.

When the evidence had accumulated on both sides for 200 years the discovery of the role of bacteria became overdue. As in similar cases, Pasteur was neither the first nor the only one to make it. Koch (1843–1910), a German country doctor, following Davaine (1812–82), studied the multiplication of the anthrax bacillus, and developed the method of growth on gelatine which made it possible to obtain pure strains—a method he used later to isolate the agents of tuberculosis and cholera. Lister (1827–1912), in Scotland, developed the practical techniques of antisepsis that began to cut down the appalling mortality in hospitals. Pasteur was, however, the main standard bearer in the war against the microbes.

Pasteur against the doctors

More by his devotion to the good of mankind and his terrific force of character than by cold scientific argument, he succeeded in breaking down the opposition to this new approach to disease, for it was a very furious opposition, comprising almost the whole of the medical profession. Pasteur needed all his early reputation as a chemist, all his acquired reputation as an industrial adviser and as a conqueror of the silkworm disease, before he could persuade the authorities of the various hospitals to adopt what are now considered the most elementary precautions of asepsis. But once he had demonstrated his results of immunization, first for anthrax in cattle, and lastly and most spectacularly for rabies in man, popular enthusiasm forced even the doctors to accept his ideas.

The foundation of scientific medicine

The revolution introduced by Pasteur was effectively the foundation of scientific medicine. In previous centuries much had been found out about the body and its behaviour in health

and disease, but this was only a half-science, capable of prediction and palliation of symptoms, but lacking the telling proof of controlling disease by effective prevention or cure. The few methods of prevention such as quarantine and vaccination, or of cure like mercury for syphilis or quinine for malaria, had been intelligent utilizations of chance discoveries or tribal traditions. But because they were not based on any scientific theory they could not be generalized and used to cure other diseases. Without the germ theory it was impossible to understand what was happening in acute infectious diseases, and doctors had to let them run their course and even helped unwittingly to spread them.

The control of epidemics : bacteriology

Once the germ theory and the technique were clearly grasped, dozens of devoted men could study an infectious disease in the field, track down the causal germ, and often, though not always, find an immunizing or curative serum, and even without this could indicate the precautions necessary to stop epidemics. Checked by improved sanitation, water-borne diseases such as typhoid began to disappear from Europe and the child-killing diphtheria to diminish. In turn the great scourges of cholera, plague, and malaria were controlled, except where poverty made the new measures impossible to apply.

The very success of the germ theory of disease in showing the way to control most of the acute diseases which decimated mankind in childhood and youth blinded public opinion, and to a lesser extent even the profession of medicine for a time, to the fact that only the advance guard of disease had been driven back, and that in treating disease, as externally caused, the reactions of the body were being neglected. There still remained the crippling disease of rickets, and the killing diabetes, heart disease, and cancer, to challenge the scientists of the next century. Nevertheless, through *bacteriology*, science had once and for all entered the field of medical practice and was soon to become an integral part of medical tradition.

The work of Pasteur and his pupils, and of the other schools of bacteriology, meant much more for science than its immediate medical results, critical as they were in the history of civilization. He had, by his earlier work, already demonstrated that even the simplest of creatures did not arise *de novo*, that no

creation of life on this earth was still going on. That these tiny organisms were alive seemed certain by their movements and reproduction. But their life must be a very different one from that of the higher organisms, a life that was essentially chemical rather than mechanical—dependent on molecular rather than on bony architecture. He was thus one of the great forerunners of the biochemical revolution of the twentieth century.

Claude Bernard and physiological chemistry

Another forerunner was also a Frenchman, Claude Bernard (1813–78), who studied the physiology of living men and animals and discovered that the important internal activities of the body were carried out by a complex balance of chemical reactions, many of which he unravelled, a balance the maintenance of which was a necessary condition for life itself. The higher the organism, the more it tended to keep its internal conditions constant and independent of the external conditions, and was thus capable of reacting when simpler organisms were frozen into immobility or cooked to death.*

Neurology

The study of the mechanism of nervous control, an aspect of physiology that had lain dormant since the experiments of Galen nearly 2,000 years before (p. 161), also came to life again in the nineteenth century. The function of the nerves both in sending messages to the muscles and receiving them from the sense organs was, thanks to the work of Bell (1774–1842) and Magendie (1785–1855),[5.77] at last understood, and their connections were tracked out through the vast complexity of the nervous system. This threw the first light on the controlling function of the most complex network of all: the brain. Even in the nineteenth century materialist biologists were casting doubts on the absolute nature of pure mental phenomena. Physiology was beginning to reveal how almost infinitely more complex were the bodies of even the simplest animals than anything the philosophers had imagined.

Scientific agriculture

Of the four sources of biological knowledge in the eighteenth and nineteenth centuries already described—natural history, medicine, agriculture, and industry—the contributions of the

last two have inevitably been mentioned in dealing with the first and second. Darwin's ideas were much affected by the practical successes of the animal-breeder and horticulturist. The early bacteriologists first secured their successes in dealing with the diseases of animals, and Pasteur himself was led to bacteriology through the industrial processes of wine-making, brewing, and silk manufacture. Nevertheless, there remains an independent stream of scientific thought which stems from the central problems of agriculture: How do plants grow in the soil, and what constitutes the food of men and animals?

From the beginning of the eighteenth century, wherever the capitalist economy had penetrated, the problems of agriculture were brought into the forefront. Venerable tradition no longer served when it was a question of getting the greatest returns from the land. Individual improving farmers banded together with progressive landlords in societies for the promotion of agriculture,[5.4] and in view of the temper of the times it was natural that science should be involved in the task of laying bare its underlying principles. This, however, proved to be a very difficult one.

Not until the mid-nineteenth century and after many false starts was it possible to go beyond the direct experience of farming practices themselves. It was a matter of trying out variations of existing methods, noting which gave increased yields, and following up promising clues. Great innovations came from industry rather than science in the form of farm machinery, which revolutionized ploughing, sowing, harvesting, and threshing. The steam-engine, however, gave far less to farming than it did to industry or transport. Complete mechanization had to wait for the smaller, lighter internal-combustion engine of the twentieth century.

The nutrition of animals and plants

It was on the chemical rather than on the biological or mechanical side that science made its most effective contact with agriculture. The pneumatic revolution in chemistry, beginning with Priestley and culminating with Lavoisier, had shown the animal organism as a kind of heat-engine burning food for fuel, and the plant as reversing the process, using sunlight to rebuild living tissue from waste gases and to restore the oxygen to the atmosphere. In Moleschott's (1822–93) classic phrase, " Life is woven out of air by light."

None of this, however, could have any practical bearing until the role of the soil was elucidated. The practical farmers and gardeners knew that the soil fed the plants, yet the scientist from 1790 to 1840 was at a loss to know how precisely it did it. Van Helmont had shown, 200 years before, that a willow tree could grow on water alone. It seemed quite reasonable then to assume that the element water had been transmuted into the element earth or wood. But after 1790 this was shown to be alchemical nonsense, and there was nothing to take its place till von Liebig's classical investigations. His report on *Chemistry and its Applications to Agriculture and Physiology* (1846), prepared at the request of the British Association (p. 392), established the division of living tissues, and consequently of foods, into the now classical carbohydrates, fats, and albuminoids (proteins). He showed that the first two were primarily fuels formed in plants from the carbon dioxide of the air, and that only the last of them contained nitrogen and were formed in plants from nitrates drawn up from the soil together with other essential elements, such as phosphorus and potassium, to be returned later to it from the excrements of animals in another great cyclic process of Nature.

Artificial manures

With the elucidation of the chemical role of the soil came the first explanation of the action of farmyard manure, and with it the possibility of supplementing it from other sources. Sir John Lawes (1814–1900), a gentleman of scientific tastes, turned his estate at Rothamsted into the first agricultural research laboratory, experimented with nitrates, phosphates, and potash from various sources as substitutes for farmyard manure, and even built factories to produce them. From this and analogous experiments in other countries came the great fertilizer industry, which in the latter part of the nineteenth century served the double purpose of intensifying agricultural production and supplementing the needs of textile chemicals in building up a highly monopolistic heavy chemical industry ready to supply the war needs of the twentieth century.

The food industry : refrigeration

Parson Malthus considered that: "In the wildness of speculation it has been suggested (of course more in jest than in earnest), that Europe ought to grow its corn in America,

and devote itself solely to manufactures and commerce, as the best sort of division of the labour of the globe." [5.54] Before his jest could be played in earnest it was necessary to send out the men to grow the food in distant lands, whether as slaves, convicts, or hunger-driven emigrants, and to find the means of getting the food back in an edible state. Traditional means of doing this certainly existed—drying, salting, boiling, and freezing go back to the Stone Age—but they could never have been used on a scale adequate to feed tens of millions, if they had not been rationalized and transformed by the infiltration of science.

On the one hand Pasteur's life-work had shown the need to exclude germs, on the other the new thermodynamics showed the way of using a heat-engine in reverse to produce artificial cold (p. 421). Canning and refrigeration between them ensured that food could be made available wherever money could be found to pay for it. It also ensured the domination of the packing and refrigeration companies over all the open spaces of the world where beef could be moved on the hoof. One end of this process has been romanticized in the cowboy and the gaucho, the other is to be found in the stockyards of Chicago or Cincinnati, where the mechanization of slaughter was to provide the prototype of the assembly line of the mass production of the next century. [6.43]

Applied biology: medicine and agriculture

By the end of the nineteenth century biology had taken its place with the older sciences of physics and chemistry as a rational scientific discipline, though it still retained many of the vestiges of earlier magical and mythical beliefs. Nor had it as yet anything like the understanding and control of its material that the older sciences had already achieved. But it was already proving its practical utility. Indeed, the great economic advances of the latter part of the nineteenth century would have been quite impossible without the help of applied biology. In fact this is one of the best examples of the Marxist dictum that "mankind always sets itself only such tasks as it can solve." [5.57,357]

The vast agglomeration of people in nineteenth-century manufacturing towns could never have been maintained without the sanitary methods which were evolved as a consequence of the gradual appreciation of the germ theory of

disease. Nor could these populations have been fed without the application of the new chemical knowledge of the nutrition of plants. The use of nitrogenous and phosphate manures was the major factor in the increased productivity of the land, and in the possibility of extending, much farther than had previously been thought possible, the areas of cultivable soil. Finally, the tropical products such as rubber and oil, so essential to the development of industry, could not have been won in the quantities required unlcss at least the worst of the tropical diseases had been brought under control.

9.6—*RETROSPECT*

Science in the age of capitalism

We have now followed in outline some of the main streams of scientific advance in the eighteenth and nineteenth centuries, and have seen connections both with the material development of society exemplified in the Industrial Revolution and its consequences, and with the evolution of thought which was needed to bring man into effective relation with his new socially created environment. It was in this period that capitalism came fully into its own, flourished most exuberantly, and began to show the first signs of decline. Science also grew mightily and continuously, apart from minor fluctuations, and its growth must have been even more rapid than that of the economy as a whole, for it occupied a far more important position at the end of the period than at the beginning. In the early eighteenth century it provided, in the steam-engine, the motive power for an industry that was still largely built on a basis of traditional techniques, and owed much to ingenuity and little to science. Towards the end of the nineteenth century new major industries based entirely on science were arising. In addition, science was permeating the older craft industries and agriculture itself. At the beginning science still had more to learn from industry than it could give to it, at the end the very existence of industry was bound up with science. Through the technical transformation of industry that it had made possible, science was affecting the development of capitalism, enabling it to turn away from the individualist free competition of small-scale industry to the large monopolist undertakings with deliberately planned and scientific production methods.

A comparison between the scientific revolution of the sixteenth and seventeenth centuries discussed in Chapter 7 and the Industrial Revolution of the eighteenth and nineteenth brings out the radical change in the kind of relation between science and economic life. In the first period, as we have seen, the call on science and its effective answer were on a very limited front, hardly more than that of astronomy and navigation. In the second the whole range of industrial activities was included: mechanism, power, transport, chemicals, and munitions. Correspondingly the science of the first period was concerned mainly with new *instruments* for the collection of information about Nature—telescopes, microscopes, thermometers, barometers—and with the mathematical analysis needed to design them and interpret their results. In the second period, though instruments continued to develop and multiply, they were now only a part of the *material* products of science. New machines—steam-engines, turbines, dynamos, electric motors, chemical plant—all designed not just to find out about Nature but to change it were the characteristic products of the eighteenth and nineteenth centuries.

Between one revolution and the other science had indeed changed from the passive to the active role, from the investigation of Nature to the "effecting of all things possible." This transition was made possible, technically by the very development of machinery, largely the fruit of joint efforts of workmen and scientists, and economically by the availability of capital in ever-increasing amounts as the profit from earlier investments accumulated. It is this strictly capitalist mode of financing technical and scientific advance that accounts for the great bursts of activity in the late eighteenth and mid-nineteenth centuries.

Compared with any previous era a prodigious effort was expended. It is only when we look at it in terms of the absolute or relative effort of today that it seems so puny. The total amount, for example, spent on scientific research in Britain in the whole nineteenth century cannot have been much more than a million pounds.[5.3] We now spend on civilian research alone seventy-five times that amount annually. The links of science with profit also account, as I have shown elsewhere,[5.3] for the highly irregular rate of that advance. Even when an application of science seemed to promise large returns, the lack of available capital for ventures that would lock it up for

some years, and could not be guaranteed success in the end, deterred all but the most sanguine entrepreneurs.

The working class and Socialism

The capitalists had used science most willingly when it served their purpose for increasing profit. They used it reluctantly and belatedly in applications for the public good, such as health and education. They absolutely refused to use it when it was a matter of examining and possibly altering the system from which they drew their wealth. But if they would not do so, others would. In the process of making science serve profit the capitalists had shown the way to the large-scale social mode of production that would make the profit motive unnecessary. They had at the same time brought into existence a working class to whom the capitalist system stood for toil, insecurity, and want.

At the outset of the period a new emergent capitalism was effectively shaking off the last vestiges of the old feudal system of production and was setting out on a career of progressive expansion. At its end, capitalism, enormously developed, had spread its dominion all over the world, but it now stood on the defensive against a newly risen working class, all but ready to move on to a new and more comprehensive socialist mode of production, and one able to use the results of science to the full (pp. 496, 836 f.).

In assessing the effects of science on life and thought over the eighteenth and nineteenth centuries, it is accordingly necessary to trace the transition from its liberating effects at the beginning, where it was allied to all the forces of progress, to its ambiguous and uncertain state at the end, where progress could no longer be taken for granted and war and social revolution loomed over the mental horizon. The dividing line came with the French Revolution and the reaction that followed it. For all their patronage, both the old régime in France and the Church and King party in Britain, with their base in landed property, had necessarily to stand against science. The advancement of science accordingly became associated in the latter eighteenth century with rising industry, political reform, and liberal theology, serving largely to justify an optimistic and progressive outlook.

After 1815 the position was no longer so simple. Science itself was deeply divided into conforming and liberal sectors,

as exemplified for instance in the history of geology and in the evolution controversy (p. 468). Its old tradition and the practical effects of its discoveries tended to identify science with the great nineteenth-century expansion of capitalism, but the identification was no longer whole-hearted or cheerful. Against it stood the evident fruits of the application of science in the blight and ugliness of industrial areas, and with it the awareness, hostile or conscience-stricken, of the mob, of the new proletariat. The spectre of Communism—however, as yet, ineffective in action—haunted the intellectual as well as the political scene. After 1870 much of the cheerfulness had evaporated and an apocalyptic note crept in.

Science in the world of ideas

The direct effect of science on the ruling ideas of the period was far less important than its indirect effect through its association with the Industrial Revolution; but it was nevertheless by no means negligible. The revolution of thought in the physical sciences of the eighteenth and nineteenth centuries was not of the same critical importance as that of the sixteenth and seventeenth. Indeed it might seem more proper to talk not of a revolution at all, but of an enormous spread of the results of the earlier revolution—as expressed in the Newtonian synthesis—first to other fields of science, such as heat, electricity, and chemistry, and then to the realm of economics and politics. The extensions in themselves were nevertheless in some sense radical innovations. Materially, it was through them that science first became effective in industry, that the natural forces of steam and electricity were harnessed, and that the transformation of matter, hitherto ruled by tradition, could be directed consciously to planned ends. In the field of ideas, if no comparable break with the past was made by the physical sciences, the extension to new fields brought out unsuspected aspects of Nature in the interaction of electricity and magnetism, and in the character of chemical reactions, and led to some grand generalizations such as the laws of conservation of mass and of energy and the electromagnetic theory of light.

Evolution as a social force

The really radical innovations were, however, to be furnished rather by the developments of the descriptive sciences, where

mathematical analysis could still find no foothold, culminating in the great Darwinian synthesis of evolution through natural selection. Darwin's own contribution came later, as the finally inescapable conclusion of long years of geological and biological observation. It would have been acceptable long before, but for the resistance of clerical and landed interests, who felt instinctively that its acceptance meant the end of any justification of a divine ordering of the world. Newton had, through his new framework of the celestial world, largely restored the credibility of design which had been so shaken by Copernicus and Galileo; Darwin struck closer home at humanity itself. As an innovator Darwin was, quite justly, compared to Copernicus. The world of religion had survived and had, indeed, almost forgotten the upset that had been caused by the break-up of the astronomical world-picture of the ancient East. But it still had the picture of creation untouched, particularly that of man himself in the image of God; whereas after Darwin there was very little left of the book of Genesis as a literal account of history. It was some time before the appropriate face-saving formulæ could be discovered, and religious truth found to be on another plane and not liable to any contradiction from vulgar facts. The suggestion that God, in his wisdom, had buried the fossils in the rocks to tempt free-thinking geologists into perdition, put forward seriously by Philip Henry Gosse, Edmund Gosse's father, was considered too far-fetched as an explanation to provide valid escape. However, as Pope Pius XII stated *ex cathedra* in 1948 that the first chapter of Genesis must be understood in an allegorical sense, the controversy must now be deemed to be over except for some Protestant fundamentalists.

The *Origin of Species* arrived at a time when its message was badly needed. It was taken up by the radical, anti-clerical wing in economics and politics, made as it was very largely in the image of its own theories of *laisser-faire* and self-help. It made possible the justification of everything that was going on in the capitalist world, the ruthless exploitation of man by man, the conquest of inferior by superior peoples. Even war itself could be justified by comparison with Nature, " red in tooth and claw." The old excuse for the dominance of classes or races, that they were chosen people or the sons of Gods, had faded, and new excuses were needed to justify their continuation in a rational and scientific world. Darwinism

provided it, although this was the last thing Darwin himself wanted.

The fundamental importance of the theory of evolution was that it introduced a historical element into the field of science, thus breaking definitely with the orthodox branch of the Greek tradition, with the eternal truths and fixed species of Plato and Aristotle, and returning to the earlier and heretical branch of the old Ionian philosophers and of Democritus, with their emphasis on rational development and change. By bringing history into science Darwinian evolution might have been the bridge between natural and humane studies, but this it failed to be because of the strong reluctance of most of its proponents to push its doctrines home. Indeed, in its stress on the kinship of man and the animals, the social evolution of humanity was obscured in favour of a purely biological one, which was in turn to lead to the absurdity of the Nietzschean superman and to the justification of race theories and imperialism.

The links between the natural sciences and the social sciences, and the full implications of history in Nature and law in society, were not to be forged as a direct consequence of the theory of organic evolution. This was to be the work of quite another movement, at once of ideas and action, that arose as a consequence of the social effect of the Industrial Revolution and to which Marx and Engels were to give a theory and a programme. Though this occurred in the mid-nineteenth century, well before the Darwinian controversy, its full meaning and consequences were not to be apparent till the twentieth century, and the discussion of it has been left to Chapters 12 and 13.

The social position of the scientist

The transition from science as a liberating idea, glimpsed at by a few choice spirits at the beginning of the eighteenth century, to a material force capable of changing the pattern of life, as it appeared to everyone at the end of the nineteenth, is not, as we have seen, one simple process, but the outcome of a conflict with many phases of alternating, rapid, or retarded advances.

In that struggle the individual scientists could not avoid being forced to consider not only the eternal order of Nature but also the consequences of successful interference with it by the new forces of technology and science. They were

inevitably torn by conflicting impulses. Drawn, as most of them were, from the middle and upper classes—for the main body were easily able to assimilate and convert such individual recruits from the working classes as Faraday—they were associated with the great movements of capitalist development. Nevertheless, as scientists, they could not but see that the results of their efforts were being used increasingly for private enrichment, and were not leading to the improvement of the general lot of man. Only a very few scientists took a conscious part in denouncing these developments. Such were A. R. Wallace and H. G. Wells in Britain, Haeckel in Germany, and the group of *intellectuals* who rallied in defence of Dreyfus in France in 1894.

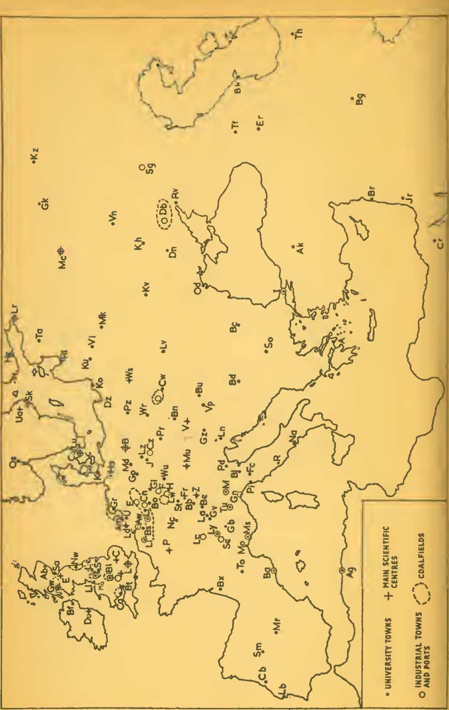
The ideal of pure science : cosmic pessimism

The majority of scientists, however, turned away from the unpleasant choice presented to them, and took refuge in a concern with the pure truths of science. They felt that if they personally were not making money out of their discoveries they were in some way free from the blame of being associated with their use for private profit.

This attitude could not fail to colour their ideas and theories even in science itself. In spite of the enormous success which scientific ideas had had in revealing the structure of the world, from the nebulæ to the human brain, and in spite of the grandiose picture which the theory of evolution offered of a continuous progress, the long-range scientific outlook became, by the end of this period, essentially pessimistic. The picture of the universe was unlighted by any conception of a humanity deliberately setting itself to master Nature for the benefit of its own and subsequent generations. It therefore tended to be one of a blind fate, leading through iron laws to inescapable death.

The limits of science

Science appeared finite. The increasingly coherent and unitary picture of the sciences that their progress in the nineteenth century had revealed seemed to the scientists a sign that science was nearing its end. In physics, the originally separate forces, light, electricity and magnetism, and heat, were all joined together in one grand electromagnetic theory. Although gravity was not understood, its agency was fully predictable, and in fact the view of Laplace, that the whole of the universe


• UNIVERSITY TOWNS
+ MAIN SCIENTIFIC CENTRES
O INDUSTRIAL TOWNS AND PORTS
COALFIELDS

Map 4.—SCIENTIFIC AND INDUSTRIAL EUROPE

To illustrate the distribution of scientific and industrial centres in Europe and adjacent countries in the eighteenth, nineteenth and twentieth centuries, Chapters 8, 9, 10. Only the major industrial towns and ports are marked. The universities shown are of very different importance as centres of science; a few of the major ones are specially marked. The older foundations cluster round the central spine of Europe, shown in Map 3. In the nineteenth and even more in the twentieth century the spread to the East is marked. For the corresponding distribution of scientific centres in America, see the insert on Map 5 (p. 932).

UNIVERSITIES

Ab—Aberdeen (1494)
Ag—Algiers (1879)
Am—Amsterdam (1632)
Ak—Ankara (1856)
A—Athens (1837)

Bg—Baghdad
Bk—Baku (1920)
Ba—Barcelona (1450)
Bb—Basle (1460)
Br—Beirut (1846)
Bf—Belfast (1845)
Bd—Belgrade (1863)
B—Berlin (1809)
Be—Bern (1834)
Bi—Birmingham (1900)
Bl—Bologna (1160)
Bo—Bonn (1818)
Bx—Bordeaux (1441)
Bt—Bristol (1909)
Bu—Brno (1919)
Bs—Brussels-Louvain (1834, 1425)
Bc—Bucharest (1864)
Bu—Budapest (1635)

Cr—Cairo (970, 1908)
C—Cambridge (1209)
Ca—Cardiff (1893)
Cb—Coimbra (1290)
Co—Copenhagen (1479)
Cw—Cracow (1364)

Dz—Danzig

Dn—Dniepropetrovsk (1918)
Du—Dublin (1591)

E—Edinburgh (1583)
Er—Erevan (1920)

Fc—Florence (1321)
F—Frankfort (1914)
Fr—Freiburg (1457)

Gv—Geneva (1559)
Gi—Giessen-Marburg (1607, 1527)
Gw—Glasgow (1451)
Gk—Gorky (1918)
Go—Göttingen (1737)
Gz—Graz (1586)
Gb—Grenoble (1339)
Gr—Groningen (1614)

Ha—Hamburg (1919)
H—Heidelberg (1386)
He—Helsinki (1828)

I—Istanbul (1883)

J—Jena (1558)
Jr—Jerusalem (1918)

Ku—Kaunas (1920)
Kz—Kazan (1804)
Kh—Kharkov (1804)
K—Kiel (1665)
Kv—Kiev (1834)
Ko—Königsberg (1544)

La—Lausanne (1537)
Le—Leeds (1904)
Lz—Leipzig-Halle-Wittenberg (1409, 1694)
Lr—Leningrad (1819)
Ld—Leyden (1575)
Lg—Liège (1817)
Li—Lille (1562)
Lb—Lisbon (1911)
Ll—Liverpool (1903)
L—London (1836)
Ln—Lubliana (1596)
Lu—Lund (1666)
Lv—Lvov (1661)
Ly—Lyons (1896)

Mr—Madrid (1508)
Md—Magdeburg
Ma—Manchester (1850)
Ms—Marseilles-Aix (1409)
M—Milan (1923)
Mk—Minsk (1920)
Mo—Montpellier (1220)
Mc—Moscow (1756)
Mu—Munich (1472)
Nc—Nancy (1752)
Na—Naples (1224)
Nw—Newcastle-Durham (1832)

Od—Odessa (1807)
Os—Oslo (1811)

O—Oxford (1167)

Pd—Padau (1222)
P—Paris (1160)
Pi—Pisa (1338)
Pz—Poznan (1919)
Pr—Prague (1347)

Ri—Riga (1862)
R—Rome (1303)
Rv—Rostov (1869)

Sa—St Andrews (1411)
Sm—Salamanca (1227)
S—Sheffield (1905)
So—Sofia (1909)
Sk—Stockholm (1878)
St—Strasbourg (1567)

Ta—Tartu
Tf—Tiflis (1920)
To—Toulouse (1229)
Tu—Turin (1404)

Ua—Uppsala (1477)
U—Utrecht (1636)

Vp—Vestprem (1952)
V—Vienna (1365)
Vi—Vilna (1578)
Vu—Voronesh (1919)

Ws—Warsaw (1816)
Wr—Wroclaw (1702)
Wu—Würzburg (1582)

Z—Zurich (1833)

INDUSTRIAL TOWNS AND COALFIELDS

An—Antwerp
Cz—Chemnitz
Cn—Cologne
Db—Donbas
Es—Essen
Gu—Genoa
Lc—Le Creusot
Lw—Ludwigshafen
Se—St Etienne
Sg—Stalingrad

Table 5.—*Science and Capitalism*

(Chapters 8 and 9)

In this table, which covers the eighteenth and nineteenth centuries, it is possible to give a more ordered presentation of scientific and technical progress. The first three columns cover political, intellectual, and economic developments. The central column combines the achievements of engineering and mechanics, leading up, on the one hand, to the development of heat-engines and semi-automatic machinery and, on the other, to the great central generalization of the nineteenth century, the conservation of energy and thermodynamics. The fourth column is devoted to electricity, which towards the beginning of the nineteenth century illumines chemical theory and as the twentieth approaches becomes more involved, through the telegraph and electric light, with the service of commerce and industry.

In column five we can trace the pneumatic revolution of the late eighteenth century and the more drawn-out, but equally decisive, elucidation of organic chemistry in the nineteenth, both linked at every turn with an expanding chemical industry. Finally, in the field of Biology and Geology, we can trace the sequence between the first classification of Linnæus and the definite establishment by Darwin of the principle of Evolution.

TABLE

Science and Capitalism

		Historical Events	Philosophy	Economics	Engineering and Metallurgy
1690			*Locke* liberty, property and toleration	Bank of England founded	*Savery* steam pump
1700	(Chap. 8.1)	War of Spanish Succession Peter the Great			*Darby* iron smelted with coke *Newcomen* steam-engine
			Berkeley idealism		
		Rise of Russia		Growth of small-scale manufacture in Britain and France	*Réaumur* theory of iron and steel
					Smeaton scientific engineering
			Hume scientific scepticism	Agricultural improvements, enclosures	
			The Philosophes		
1750		Frederick the Great	*Diderot* "Encyclopédie" *Voltaire* The Enlightenment	Beginning of the industrial Revolution	
1760	(Chap. 8.2–8.4)	British conquest of India	*Rousseau* "Social Contract" Lunar society in Birmingham		*Roebuck* Carron iron works *Black* latent heat
		American Revolution		*Adam Smith* "Wealth of Nations"	*Hargreaves, Arkwright, Crompt* cotton spinning machinery
			Kant philosophy of duty	Capitalism and the Factory System	*Boulton* metal factory *Wilkinson* ironmaster Watt rotary engine *Cort* wrought iron
		French Revolution	*Goethe* Natur-philosophie		
				Malthus on population	*Rumford* heat from work
1800	(Chap. 8.5–8.6)	Napoleonic wars			*Trevithick* high pressure engine *Bramah, Maudslay Whitworth,* machine tools
		Holy Alliance Peace and reaction	*Hegel* dialectical idealism	*Bentham, Mill,* utilitarianism	
		Reform, triumph of bourgeoisie		Railway Age	*Stephenson* locomotive
			Comte positivism		*Carnot* principle of reversibility
1850		Year of Revolutions	*Marx* and *Engels* "Communist Manifesto" Dialectical materialism "Capital"	Britain workshop of world	*Meyer, Joule, Helmholtz,* CONSERVATION OF ENERGY *Bessemer* cast steel
	(Chap. 8.7)	American Civil War			
		Franco-Prussian War Paris Commune		Great depression	*Lenoir* gas-engine *Siemens* open hearth *Otto* four-stroke cycle *Gilchrist* basic lining
		Rise of Germany	*Mach* neopositivism	Rise of Socialism	*Clausius, Gibbs* thermodynamics *Parsons* turbine
1900		Colonial Imperialism			

5

(Chapters 8 and 9)

Electricity	Chemistry	Biology and Geology
		Camerarius sex in flowers *Woodward* fossils relics of Flood
Hauksbee frictional electricity	*Stahl* phlogiston	
		Boerhaave teacher of medicine
Gray **electrical conductivity** *Dufay* two kinds of electricity	*Hales* begins the pneumatic revolution	*Linnæus* **classification, "System of Nature"**
Musschenbroek electric condenser and shock *Franklin* **+ ve. and − ve. electricity, lightning conductor**	*Lomonosov* physical chemistry *Black* carbon dioxide	*Trembley* invertebrates *Buffon* **" Natural History " " Theory of the Earth "** *Haller* physiology
	Priestley, Scheele discover oxygen	
Coulomb laws *Galvani, Volta* **current electricity**	*Lavoisier* **reverses phlogiston theory, founds modern chemistry**	*Werner* cataclysms *Hutton* **geology without miracles**
Davy electrochemistry	*Dalton* atomic theory *Haüy* crystallography	*Bichat* tissues *Lamarck* evolution by modification *Oken* morphology *Cuvier* palæontology *W. Smith* geological map
	Berzelius inorganic chemistry	*Bell, Magendie* nervous system *Baer* embryology *Lyell* **" Principles of Geology," uniformitarianism**
Oersted, Faraday **electromagnetism** The telegraph	*Dumas* *Liebig* *Pasteur* *Kekule* *Van't Hoff* **founders of organic chemistry**	
Maxwell **electromagnetic theory of light** Wilde dynamo	**Mendeleev periodic table**	*Liebig, Lawes* agricultural chemistry Evidences of ice ages, and of primitive man *Mendel* heredity *Darwin* **" Origin of Species " EVOLUTION by selection** *Pasteur* **germ theory of disease** **Antisepsis, immunization**
Edison electric light	Manufacture of dyes and explosives	
Hertz radio waves		

consisted of particles whose motion would be known for all eternity if it were known at one moment, justified a picture of fate more all-inclusive than any the Greeks had had. In chemistry the elements had nearly all been discovered. Mendeleev's great generalization had even shown how many of them there could be, and how few were still to be found. In biology the Darwinian theory had shown that evolution itself had become a fatalistic progress of chance and struggle.

Of course there was still very much for science to do; each scientist in his own field saw an unlimited future of detailed discovery before him, for, oddly enough, in spite of these great generalizations of theory, science had become more specialized at the end of the nineteenth century than it had ever been before or was to remain after. Specialization itself was a way of escaping the too heavy burdens of a general view of the universe. Cosmic pessimism was balanced by confidence, if not complacency, about the present state and immediate prospects of science and society.

Whatever they felt about their own subject, nineteenth-century scientists knew that the general framework of scientific theory was secure, that the heritage of Newton had been largely fulfilled, and that the odd phenomena which did not seem to fit with this classical picture would no doubt turn out to be explainable if only someone with sufficient ingenuity would tackle them. In exactly the same way they agreed with the sentiments of the people among whom they mixed who felt that the order of society—the stock exchanges, the freedom of enterprise, the freedom of travel and trade—were, if not absolutely realized now, on the point of being realized, and that an era of indefinite intellectual and material progress was at hand. There were, of course, clouds on the horizon: labour troubles, an unpleasant increase in general armaments; but with good sense, and a realization that it was to the advantage of everyone to maintain a peaceful capitalist economy, they hoped the clouds would pass away. The future, they felt, must needs be a magnified but rather uninteresting prolongation of the past. These expectations, both in science and in society, were doomed to be disappointed in a way that we now know only too well. The twentieth century, as we shall see in the ensuing chapters of this book, was to open great and new perspectives for science and society.

PART VI
SCIENCE IN OUR TIME

INTRODUCTION

THE TWENTIETH-CENTURY BACKGROUND: THE REVOLUTIONS IN SCIENCE AND SOCIETY

As we reach our own times history blends into remembered experience. Here we are close to the events, are watching struggles still unresolved, with their protagonists still alive and active. All this makes it especially difficult to comprehend what is happening, to analyse and judge the significance of the movements of science and society. Yet despite this the effort must be made, for while it may suit historians in general to avoid dealing with recent periods until time allows disinterested appraisal, that is doubly impossible here. A book that sets out, as this one does, to show the connections between science and social forces can be useful only if it can show how those relations, as we find them here and now, have arisen out of their previous history. No gap can be allowed between present and past. But to omit the story of science in the twentieth century would exclude the most important part of the whole argument, for it is in this twentieth century that science has come for the first time into its own. Far more scientific work has been done in the last fifty years than in the whole of previous history. And this is no mere quantitative growth; at the same time there has been greater advance in the knowledge of the fundamental nature of matter, animate and inanimate, than in any comparable period in the past. We may reasonably speak of a second *scientific revolution* in the twentieth century.* Further, and this touches more closely the purposes of this book, for the first time in history science and scientists have been involved directly and overtly in the

major economic, industrial, and military developments of their time.

The problem is no longer, as was the case in the earlier chapters of this book, to demonstrate how science has affected the course of history. The effects of science in the past were real enough, but they had to be sought for. The danger had been that science would be thought of as an appendage—interesting, brilliant, but remote from the main stream of history. Now, half-way through the twentieth century, the danger is the opposite one, that of giving science too much credit for good or ill in the tremendous and disturbing changes, the wars and revolutions, that this century has already witnessed.

It is no accident that the revolutions in science and society should occur together, but it would be too simple a view to make either one the consequence of the other. The interactions have been far more subtle and reciprocal, and their disentangling will be the main task of the remaining chapters of this book.

What need to be sought out, at every major turn of events, are the social and economic forces that have helped to determine the general directions and speeds of scientific advance, and conversely, the points at which scientific discoveries have come to modify profoundly the course of economic and even political events.

A time of transition

The events, terrible, rapid, confusing as they have been, are not without a general pattern. We are living in an age of transition from one kind of society to another, in the middle of conflicts still unresolved. The division of the world which first appeared in 1917 is an index of the sharpness of the contrast between the old and new forms, but it only brought out into the open conflicts already latent in the apparently uniform society of the nineteenth century. However differently people may feel as to the explanation and the outcome of the struggle, no one can deny its existence. The whole system of *capitalism*, first established 300 years ago, is now being challenged by another, *socialist*, system which has arisen out of the inner conflicts of capitalism itself.

For most of the twentieth century, however, it is not the open challenge represented by the existence and growth of the Soviet Union that has been the main determining factor

in world history. It is rather the continued working of forces from an earlier time. Two of the decisive events of the century, the First World War and the great slump of 1930, were the products of political and economic difficulties wholly inside capitalism, and so were both the preparations and the early stages of the Second World War. The evolution of capitalism went on for the whole period and it is still the dominant economy over a vast, if diminishing, portion of the world.

The evolution of the socialist part of the world, first in Russia alone and now in China and in many other countries, has necessarily been of a different kind. Partly on account of the initial poverty of the countries and partly because of the hard struggles that have had to be waged to build up a radically new economy, in the face of continuous interference from external enemies, it is only in very recent years that the socialist countries have begun to claim a leading part in world economy, technology, and science.

Nevertheless, in spite of this lag, the importance of the developments in the socialist countries is far greater than their mere scale would indicate. They represent a new kind of way of employing natural and human resources which is impressing the workers of capitalist countries and even more the peoples of the under-developed countries. These have won some measure of political freedom and are now demanding effective economic liberation, an additional and powerful element in the transition from capitalism.

Monopoly and imperialism

In the capitalist world the major feature of the twentieth century has been the rapid growth to complete dominance of large combines, trusts or cartels, partly commercial, partly industrial. Even their names are familiar all over the world—Du Pont, General Motors, Krupp, Schneider Creusot, Imperial Chemical, I.G. Farben, etc., not to mention the nominally dispersed empire of Standard Oil or the wide range of Morgan interests. The tendency to monopoly, already evident in the late nineteenth century, has in the first place an economic source. Trusts, exercising partial or complete monopoly, had great advantages over small competitive firms in securing profits, no longer at the mercy of market fluctuations, and in tiding over bad times. They were also favoured by technical factors, such as the development of the internal-combustion engine creating the

motor industry and providing in turn vast markets for a new oil industry. The technical innovations themselves, such as mass-production, raised the amount of capital necessary for manufacture on a scale large enough to be profitable to a level only monopoly firms could reach. Finally, science itself has helped the formation of monopolies through the same requirement of large capital outlay. The industries mainly or entirely founded on science, such as the chemical and electrical industries, were monopolistic from the start. As a consequence, as we shall see (p. 896), some eighty per cent of industrial science is carried out in the research departments of monopoly firms.[6.35; 6.36]

The very existence of trusts and cartels provides protection for prices well above the competitive level. This, combined with the reduction in costs obtained by large-scale production, making fuller use of engineering and scientific research, has helped the monopolies to secure ever greater profits. They have consequently been able to increase in range through mergers and new ventures. Their network of control, only part of which is ever made public, puts them in an apparently unassailable economic position. As productive enterprises they undoubtedly mark an improvement on the small traditional, rule-of-thumb firms that they broke or absorbed. Nevertheless experience has shown that they are no better able to escape the nemesis of all production for profit. The greater the efficiency of exploitation of labour they have achieved the more difficult it is to find consumers from among those same workers for the goods they produce. It has been the need for new markets and for the protection of those already acquired that has led monopoly interests virtually to take over the functions of government to further their own purposes (p. 794).

From 1880 onwards government policy, particularly foreign and colonial policy, has largely been dictated by the urge to secure greater and greater shares of the world markets for the products of monopoly enterprises, especially in the exports of such capital goods as steel and machinery. This is the pattern of *imperialism*—once proudly flaunted, now a reproach which needs to be explained away—which in one form or another, under the Union Jack or the Stars and Stripes, remains the dominant form of capitalism.

Despite arrangements arrived at from time to time to share

out the markets of the world among the monopolies of different countries, these could not be lasting and rivalries tended to increase. Whenever the allocation of markets seemed no longer to correspond to the real strength of the powers, the only means of changing this was military force. Hence the many wars, small and large, which have plagued the world these last seventy years. War and war preparations have also themselves been an essential outlet for the products of the most powerful monopoly firms in the steel and chemical industries. They have provided unlimited orders and no excessive scrutiny of prices. Nevertheless, whatever advantages war has brought to the monopolists of the successful countries in the way of increased markets, the fundamental difficulty of disposing profitably of the products of industry remains, and crises of a severity unknown in previous ages have been the only alternative to war. To some extent the Cold War has been a substitute, but as it passes into a period of competitive coexistence it will be difficult once more to provide for profitable production.

These brief paragraphs may serve as an introduction to the political and economic background of our times. A more critical appreciation is reserved till after the discussion of the social sciences in Chapter 13 (pp. 888 ff.).

The place of science and technology in the era of monopoly

The tightening of the links between monopoly, imperialism, and war has had the further effect of bringing governments, whose primary responsibilities and greatest expenditure are on armaments, directly into the development of new weapons to be manufactured by the big monopoly firms. These weapons —jet planes, guided missiles, ballistic rockets, atom and hydrogen bombs—are becoming increasingly scientific, not only in original invention, but in constant subsequent improvement. They consequently involve governments in scientific research and development, growing at an enormously rapid rate. Military research expenditure already vastly overshadows not only that on pure science, but also even that on industrial research (p. 585).

The effect on science of the nationalization of industries has been a very minor matter in comparison with its military commitments. This is due to the fact that as these industries were unprofitable under private enterprise very little research was done on them, and that now, under nationalization, it is of a

very low priority. On the other hand the virtual taking over of the finance of universities by governments in Britain, and even in the citadel of free enterprise, the United States under pressure of defence research contracts, has made an enormous difference to the status of research. Although for the time being the control exercised over research, at least in Britain, is very indirect, it does in fact mean that the general direction of fundamental research has now passed into governmental hands.[6.7; 6.14]

While these processes of concentration of power were taking place the independent competitive capitalists who dominated the nineteenth-century economies were rapidly being submerged. It is not that there is no room for the small man. Actually the ancillary requirements of modern large-scale industry offer opportunities for innumerable sub-contractors and component suppliers. It is rather that their relative importance has shrunk; they depend on the big firms; they have become clients and have lost their independence. The same loss of status has befallen the inventors and amateur scientists who played such a large part in advancing science since the seventeenth century. From now on scientists and technologists alike, together with most of the doctors, have ceased to be professional men in the old sense, exercising their skill for fees or working on their own account, and have become employees or executives of government departments or large firms.

This change, which has come about, at first gradually, then very rapidly during and after the Second World War, is bound to have a profound influence on the attitude of scientists not only as individuals but also in relation to their work. It creates a deep conflict between their immediate dependence on their source of livelihood and their responsibility for the safeguarding, advancement, and use of science, a problem to which we shall return later (pp. 897, 912 f.).

Science in a socialist economy

So far I have discussed only the economic trends that have affected science in capitalist countries. Its development in the Soviet Union and in other countries that have taken decisive steps towards socialism has been very different. There, where all major industries have been taken over by the State, where there is neither monopoly nor competition, there is a deliberate and conscious drive to develop and use science to the full.

This has been achieved not by subordinating science to the industrial and agricultural organizations that have there taken the place of private firms, but rather by using the old academies (p. 901) and turning them from the honorific societies they had become into active centres of research and higher teaching. It is the scientists, grouped in the academy and its institutes, who plan this work, with the object of securing at the same time the most fruitful intrinsic growth of science and the maximum of help that can be given to the full utilization of natural and human resources. This will be referred to again in connection with various aspects of scientific work (pp. 573 f., 668 f. 820 f.).[6.10; 6.30; 6.54]

Interactions of industry and science

Modern industry is permeated by science, and in certain lines, such as electricity and chemistry, it is largely a scientific creation. It is therefore no longer relevant, as it was in earlier times, to describe the specific characters of industry and to follow with their influence on scientific thought. The degree of inter-penetration is already too great. It is only worth attempting to bring out the general character of the influence of technology on science and to illustrate particular interactions as they arise in later chapters.

The technical developments of the twentieth century already indicate that we are in the presence of a second or rather third major industrial revolution (p. 590). The comparison may, however, obscure the fact that it is a revolution of a new kind, one in which planned scientific research is taking the place more and more of individual mechanical ingenuity. Further, while the great Industrial Revolution was concerned largely with the production and transference of force, relieving men, in principle, from hard muscular work, the twentieth-century revolution is largely in the substitution of the machine or electronic device for the skill of the worker, and should relieve him from the burden of monotonous clerical or machine-minding tasks.

Although the first steps to such a revolution have been taken in the development of automatic and servo-mechanisms, this has been only a recent achievement. The earlier features of twentieth-century industry were more in the line of expanding and extending into new fields the devices of the nineteenth century. The impulse to the direction of twentieth-century

technology is provided by the special profitability of the mass media of transport, communication, and entertainment.

In transport the motor-car, the tractor, and the aeroplane were made possible in the first place by the internal-combustion engine—itself a nineteenth-century development. These substituted for the rigid and limited facilities of the railway the flexibility and range of millions of small units that could go everywhere and do anything.

To make these for a great, new, low-price market meant the rapid spread of mass-production methods. The motor-car and the motor industry called in turn for vast extensions in the production of petrol, rubber, sheet steel, and plastics, which promptly found a multitude of other uses. A new engineering and light industry grew up in which centrally generated electricity took the place of the stationary steam-engine, and this, together with the entry of electricity into the home, created a new heavy electrical industry. Less important economically, but more noticeable and carrying a larger contribution from science, were the new electrical communication industries of radio and television and the exploitation of photography in the cheap Press and the cinema.

This catalogue unfortunately cannot be exhausted with the peaceful uses of technology. The aeroplane has had, almost from the outset, a primarily military objective, from which civil aviation can take some pickings. War is also responsible for the multiple refinements of electronics in telecommunication and radar and for the new lethal interest in atomic energy.

Underlying the mechanical and electrical devices, though far less conspicuous, has been the rapid growth of a new all-pervasive scientific chemical industry producing everything from fertilizers to detergents, from nylon to antibiotic drugs. It was ready to turn out explosives and gas for war, and now it has become a mainstay of atomic and power production.

Power and control

The multifarious productions of science among which we live more and more of our lives depend largely on the use of two very general and extremely important new technological principles. The first is the availability of *power* in adequate quantities just where it is needed, whether in beating an egg in the kitchen, turning a twenty-ton casting in a factory, or cutting down a tree in the distant forests. This service which

electric grids and the ubiquitous petrol engine provide between them is one reason for the more than five-fold increase in productivity per man hour that has been achieved in the last fifty years in the United States.

The second principle, likely to be even more important in the future, is that of precise and increasingly *automatic* control of all industrial operations, whether mechanical or chemical. Many chemical plants have already become fully automatic, with electronic devices keeping all the variables in control. In engineering, fabrication and assembly lines are well set on the same path. Between them, these two principles imply ever-increasing strength and skill which science makes available to industrial processes as a whole, thus supplementing and extending without limit the range of the craftsman's arm and brain. Of the two, the first is but an extension of the mechanical power of the Industrial Revolution. The second is something radically new, an extension of human senses, nerves, and brain by electrical means, and, through the unlimited range of the combinations it can offer, is bound to have unpredictably greater material and social effects (p. 590).

These developments are now beginning to make themselves felt. Atomic power and automation have arrived. In earlier stages the major changes have been due to the increased size and concentration of plant. It is this that has made possible the multiplication of industrial research laboratories which range from mere testing shops to almost university rank. What occurred quite exceptionally in the late nineteenth century (p. 402) is now the rule. Science has now won a definite place in industry. This, combined with the growth of similar laboratories in the government service, means that the interaction between science and the productive processes generally has now become much closer and more important. It has indeed become something radically different in the twentieth century from what it was in earlier ages: it is on a larger scale, it is much more rapid, and it is becoming a fully conscious interaction.

The scale of scientific advance

The scale of scientific effort has in the twentieth century increased almost out of recognition. In 1896 there were perhaps in the world some 50,000 people who between them carried on the whole tradition of science, not more than 15,000 of whom were responsible for advancing knowledge by research.

Fifty-eight years later there were at least 400,000 active research workers, and the total number of scientific workers in industry, government, and education is almost impossible to assess accurately, but must approach two million people. The expenditure on science has increased in far greater proportion, from less than half a million to more than £2,000 million, an increase of 400 times allowing for the change in the value of money. This implies an average rate of growth of ten per cent per annum.[8.54] The rate of increase in the last few years has been much greater, up to twenty-five per cent (p. 585). Such rates of growth are far greater than those of any other element of society, greater even than that of military expenditure. Science, however, is still a long way behind, for though some ninety per cent of scientific expenditure is for war research and development, this is only twelve per cent of military expenditure.

Such a rate of growth betokens more than a mere change in size, it is in itself an index of a profound change in the character of science and in its relations to society. Of that change there are ample indications from inside science and in the ever-growing dependence of industry and government on science. That dependence has become completely reciprocal. Not only has the total cost of science increased out of measure, but so also has that of its separate components. Even apart from the multi-million-dollar machines, now indispensable in many fields of physics research, ordinary laboratory costs are beyond the purse of all but the wealthiest individuals or even of most teaching institutions, forcing dependence on big business or government.

Another significant feature of the transformation is the change in geographical location. In 1896 practically the whole of world science was concentrated in Germany, Britain, and France, the remaining centres of science in Europe and America being in effect subsidiary local branches of the science of those countries, and there being comparatively little science in Asia and Africa. By 1954, while the science of the old centres had grown considerably but unevenly, that growth was quite eclipsed by the enormous development of science in the United States and the Soviet Union. Japan, India, and China are now making substantial contributions to the advancement of science, and its spread to the remaining colonial world can hardly wait for the removal of imperialist restrictions.

A world science is indeed in process of formation, and one consciously linked from the very start with the expansion of industrial and agricultural production. It should be noticed also that though the philosophy of science differs widely between socialist and capitalist countries, as also do the major uses to which science is put, both types of system have come to need science more and more urgently.

The rapidity of application in science

The third characteristic of science in the twentieth century is the far more immediate and rapid application of scientific discoveries. Although it still remains true that the science on which the bulk of twentieth-century technique is based is nineteenth-century science—in power production, in electricity, and in chemistry—inventions depending entirely on more recent discoveries have made their impact in minor but striking roles. Radar and television, plastics and artificial fibres, synthetic vitamins, hormones, and antibiotics, all are but the first samples of what will come from the great scientific revolution of the twentieth century, and so also, if we are not careful, will the large-scale use of atomic and hydrogen bombs, radioactive and bacterial poisons. These are just examples of a principle more important than all of them put together, that of the universal possibility of using natural science, immediately or with a delay of a few months or years at most, in the formulation and solution of any problem in practical life. What happened almost by chance in the nineteenth century, or was brought about by the genius and force of character of a solitary inventor like Bessemer or a public-minded scientist like Pasteur, is now a recognized and almost routine way of tackling industrial, agricultural, or health problems.

Indeed, we have reached the stage at which it is foolish and self-defeating to leave such problems to the old stand-by of chance or rule of thumb. Research and development have become recognized disciplines embodied in rapidly growing institutions. Science has now entered industry in an intimate and operational way, and in doing so has been both enlarged and transformed. Nor has the development stopped there. The increasing scale of scientific application and the urgency that war and war preparations impresses on it have involved science ever more closely with governments, while in the newly established socialist countries science is necessarily invoked

from their very inception in every constructive scheme. It is from this experience of science that has grown a new consciousness of its power as an agent in social transformation. A modern community has come to depend on science for its very existence. We are beginning to see in this century the realization of the hopes of the men of the seventeenth century like Descartes, when he declared that through science we could "become the masters and possessors of Nature" (p. 310).

Today we are participating in the culminating point of the revolution which such men as these started 400 years ago. It is one which is comparable in importance with that which ushered in the first human societies; it is even greater, because of the unlimited further prospects it offers, than that which followed the invention of agriculture. It is now apparent that man is about to reach a state in which he can control his material environment through the conscious use of science. He can secure himself against want, abolish tedious toil, and by rapid stages reduce the misery of disease. How far this will be done is now seen to depend squarely on man's ability to adapt his social forms to provide the co-operation that is needed to secure these aims and to overthrow the interests that stand in the way. Thus the science of human society and of its laws of transformation comes to occupy the central place in the determination of the future.

The power of science to affect the life of man for good or evil is no longer seriously in doubt. The problem now is rather that of finding the means of directing science to constructive and not destructive ends. This, however, is a problem much greater than any in the particular sciences which we are considering. We will return to it at the end of Chapter 14, when considerations from the physical, biological, and social sciences can all be brought to bear on it. Here it is sufficient to consider the more immediate and practical question of the most rapid utilization of science or of the means of closing the gap between scientific ideas and their practical utilization. This gap, which was formidable in the nineteenth century, existed for reasons that were primarily economical and not technical (p. 440). It took the abnormal conditions of the two great world wars to prove in practice that it could be narrowed, and to show the way this could be done even in peace.

Effects of war on science and scientists

The First World War, which fostered the development of the bombing aeroplane, the tank, and poison gas, gave some foretaste—an exceedingly bitter one—of what science could do in war. By bringing scientists and practical men directly together with the incentive of military requirements and relatively no restrictions on funds, it forced the recognition that there was no need to wait for years before putting an idea step by step through experiments and trials into full production. This lesson was no sooner learned than it was largely forgotten, as witness the slow pace of the development of such obvious winners as the jet engine (p. 565) and television (p. 546) between the wars. The Second World War was needed before the lesson could be accepted and acted on. The first spectacular proof of this was the production of the atom bomb—from the scientific discovery of atomic fission as a hardly detectable effect in 1938 to a death-dealing horror in 1945, with the expenditure of more money than science had used in the whole course of human history up to that time (pp. 536 f.).

Science and planning

War produced the most outstanding example of the conscious use of science in the twentieth century. In all fields of industry and agriculture this new integrated approach began to be used. Indeed, it was from the outset the policy of the new socialist society brought into being by the Revolution of 1917. Industry, agriculture, medicine, and even science itself began to be planned instead of being left to the chance of economic forces. For all their overt disapproval, industries and governments in capitalist countries began to copy the Soviet Union in its tendency to plan. In the light of experience of successes and failures it began to be seen that the applications of science did not just come of themselves, but that human needs had first to be discovered and that then deliberate and planned scientific effort was needed to find the means to satisfy them. This dawning consciousness of the function of science was one of the most characteristic features of the twentieth-century social revolution. It corresponded with an equally far-reaching, but as yet also incomplete, revolution inside science itself.

The great and terrible events of the time—crises, wars, and revolution—whatever they might import to the main ends to

which science and technology were used, were, as we all know, quite compatible with a great new efflorescence of science. The stream of new discoveries and inventions, the depth and range of the new scientific theories are, however, for all their novelty, but continuations of internal movements of scientific experiment and thought that have been progressing ever since the Renaissance. The inner nature of the advance of science in our time can be accounted for by reasons drawn from the internal history of science, though even here the influence of external factors has often been great. Nevertheless, the unprecedented *scale* and *speed* of the whole movement are linked directly to technical and economic factors. So also are the general *strategy* of advance and the relative effort devoted to the different fields of science (p. 919).

Science pays its way

The major and decisive fact is that, starting in the 'nineties, and with a momentum rapidly increasing in the First and Second World Wars, science began to pay its way. It became, fully consciously and immediately, what it had long been unconsciously and incidentally—an essential part of production. It was something worth investing in, directly by setting up research laboratories or indirectly by subsidizing universities where the workers for these laboratories could be trained and where basic research, of use to all, could be carried out.

In the course of fifty years a complete transformation of the position of science in society was effected, in which three stages are already distinguishable. At the beginning of the period, in the 'nineties, we are still in the era of *private* science, that of the small laboratory of the professor or the back room of the inventor. The next stage, first evident in the 'twenties and 'thirties of the new century, is the era of *industrial* science, that of the research laboratory, spending a few tens of thousands of pounds, and of the correspondingly expanded university departments and the now subsidized research institute. The third stage, appearing first in the Soviet Union but becoming universal in the Second World War, is that of *governmental* science, where the expenses of research and development run into hundreds of millions of pounds and establishments as large as towns are needed to house the men and equipment needed for it. For this only the State can find the money, though it may call on the assistance of monopoly firms, themselves almost

States in their own right, to spend it for them in the form of development contracts.

With each increase in the scale goes an increase in the scope of the application of science. In the first stage it is for detailed improvements and small devices. In the second it is for whole new scientific industries—for radio or fine drugs. In the third stage science reaches the greatest enterprises—the war production that has been made the focus of State capitalist enterprise; or the great constructive and Nature-transforming projects of socialism.

Science and everyday life

With this expansion of scientific effort has gone a two-pronged extension of science into the processes of industry and into the apparatus of daily life. Science is at the same time becoming more useful and more familiar. Every phase of industry and agriculture is now permeated with science, and more and more consciously so. Scientific instruments are used, and scientific concepts are replacing immemorial traditions on the bench and in the fields.

The same tendency now spreads to the home. Not only are the most elaborate scientific devices, such as television receivers, becoming familiar, but in the daily routine of cooking and washing, in the care of children, in the preservation of health and beauty, the products and the ideas of science are making their way. Not all the deceits and fables of advertising are sufficient to prevent the spread of a new serious and exciting interest in science. Indeed this interest produces in turn a practical impetus to science. The popular market for scientific gadgets is becoming a major source of profit, and this helps research; while the popular interest in science itself has brought into being a new profession of *scientific journalism* and an avidly read *science fiction.*

The strategy of scientific advance

These general considerations, while they go some way to explain the rapid increase in the scale and tempo of science during the century, need to be examined more closely before any account can be given of the particular directions taken in the sectors of scientific advance. Only in certain cases, and these not the most important scientifically, have economic needs had an immediate effect on the advance of specific

sciences. An example is furnished by the dependence of the study of atmospheric electricity on the development of wireless communication and the subsequent application of the principles of reflection in radar (p. 545). More commonly the impulse has been given by the inner developments of the sciences, and these have blossomed out wherever these developments have found extensive and profitable applications in peace or war. Examples are the wide search for antibiotics following the isolation of penicillin (p. 643), and for the atom bomb following the discovery of nuclear fission (p. 537). This type of relation between science and society, in earlier times, has already been described. What marks out the twentieth century is both the enormous scale of the industrial activities based on science and the rapidity of the interactions between scientific and technical advance. What some of those interactions were will be shown in outline in the succeeding chapters.

The scientists' reaction to historical events

The effects of internal developments in science and those of technical and economic factors are, however, not even together enough to account for the character and the spirit of the twentieth-century advance of science. Much weight must be given as well to the influence on the minds of the scientists themselves of the great events among which they lived, and the material and moral problems which their increasingly important participation and responsibility brought to them personally. Such influences were general and not specific, and it is impossible to attribute to them particular advances in science. They did, however, tend to draw workers to or repel them from such disputable fields as nuclear physics and micro-biology in the measure that these became identified with atom bombs or bacterial warfare.

The most prevalent reaction of the scientists was to bar uncomfortable facts from their consciences, but this process itself meant turning their scientific interests in a more abstract or, as they would have put it, in a more purely scientific direction. The increasing insistence of some scientists on the purity and freedom of science is itself an indication of an uneasy conscience as to the social consequences of their work and as to the effects of social changes on the future of science itself (pp. 912 f.). On the other hand, a small but increasing number saw and welcomed the break-up of the old order, and understood how

science itself could be a liberating force, both in its indirect effects through transforming industry and directly by widening all men's minds and giving them a greater possibility of realizing their capacities. As a result of these diverging tendencies science was torn with conflict, but that in itself may actually have assisted its progress, because science has always grown on criticism, and especially in the twentieth century no theory or dogma was safe. Internally science was being attacked as a result of its own inconsistencies, and externally the scientists were being more and more dragged into the economic and political struggles of the time.

The rise of Nazism

Until 1933, despite the upsets of the First World War, scientists as such had enjoyed a secure and to some extent privileged position nationally and internationally. Their work for the establishment of truth and the benefit of mankind was supposed to set them above the common conflicts of States and classes. With the coming into power of Hitler they were struck by the first wave of persecution, itself based on a perversion of science which had been used to justify religious prejudices in earlier times. The Nazis, inspired by their racial theories, first struck at the livelihood of Jewish scientists, then at their scientific beliefs, and refugee scientists of distinction appeared in many other countries, carrying with them their valuable learning and also some of the philosophy and prejudices of the German intellectuals.

Twelve years of Nazi power, culminating in a devastating war and the insane scientific slaughter of tens of millions of helpless people, should have been enough to demonstrate to the men of science, no less than to others, the dangers still inherent in the irresponsible greed of capitalism and the need to take steps to prevent their recurrence. But the very enormity of the disasters and the fears for the future that they engendered, powerfully seconded by security and loyalty tests, have had a paralysing effect on the majority of scientists in capitalist countries. They saw themselves as part of a vast machine with the knowledge of what it could do but without the power to arrest its motion. The attitude of conformity, from which only a minority have escaped, cannot be limited to political or economic matters; inevitably it has coloured the character of scientific thought, making it at all points

more cautious, vague, and mystical, and above all pessimistic (p. 790).

Scientists in the socialist world

The attitude of scientists in socialist countries has been polarized by their experiences in a different direction. On the one hand they have suffered from the remorseless devastations of Europe and Asia, which have wiped out the fruits of years of painful effort and sacrifice. Through their experience they have learned something of the frustrated hatred which they inspired among the leaders of the capitalist world. On the other hand they have been inspired by hope, by the capacity for recovery and renewal that the peoples of the devastated lands have shown, and by the sure prospects, given peace, of far greater achievements than before. One effect of this has been to produce a critical, often violently critical, attitude to all aspects of science, theory as well as practice, that seem associated with the destructive and limiting character of capitalism. At the same time it has generated a positive belief in the capacity of the human mind to understand and control Nature that rejects in advance all intrinsic limitations. These attitudes found positive expression in important constructive scientific work. At the same time they had unfortunate negative results. Partly due to the external stresses and partly to certain abuses of the Stalin regime, a dogmatic spirit spread into science in the Soviet Union and countries influenced by it (pp. 832 f.). This led to controversies, of which one, that on genetics, is discussed later (pp. 667 f.). This had damaging effects on Soviet science and alienated many scientists abroad. The same tendencies led to an over-estimation of national achievements and a corresponding disparagement of scientific achievements in capitalist countries (p. 826). These tendencies, however, appear now to have been temporary aberrations of the Cold War period and are being markedly diminished in the present atmosphere of relaxation. Scientific exchanges are multiplying between capitalist and socialist countries on a give-and-take basis, especially in the decisive field of atomic energy. This does not mean that no differences remain. However, they are no longer in the field of science itself, where the appeal of logic and experiment provide for necessarily provisional agreement, but rather in that of philosophic theory, where ideological influences of social and historic

origin play a larger part. Though the different experiences of different cultures does in this way give rise to contrasting ideas as to the nature and purpose of science, the conflict between them may illumine the underlying forces of a world in a state of rapid transformation.

Phases of transformation in the twentieth century

The way in which economic and political factors interacted with the development of science will become clearer and more concrete when discussed in relation to the progress of the different branches of science, and this will be attempted in the following chapters. This treatment inevitably breaks up the time sequence, but science has grown so multifarious and is advancing so rapidly that less is lost than would be if an attempt were made to break the period down and, as in previous chapters, to discuss the progress of the whole of science in each period. The events are, however, so recent and so fresh in the memory of most of the readers of this book that it should be sufficient first to recapitulate them very briefly, and then to call attention to them section by section as they arise. This is all the easier in that, perhaps more than any other time in human history, our age is divided up by sharp breaks which mark off very definite phases, each with its characteristic features. The two great wars, with their immediate aftermaths of revolution, block out the early century. They are major events in science as well as in human history.

Before the First World War came, world-dominant capitalism had reached its last stage—the wealthy, peaceful, but increasingly troubled age of imperialism. Between the wars came the establishment of the Soviet Union as a viable economic unit and the great economic crisis of capitalism, with its aftermath of Nazism. After the Second World War, and the triumph of liberation movements in Europe and Asia, reaction gathered itself together and the "Cold War" was declared. Now this period is yielding to one of peaceful coexistence of the two systems as the result of a nuclear stalemate and the manifest reluctance of the peoples of all countries to be involved in another and even more destructive war (pp. 775–777), though as long as the world contains two hostile armed camps and atomic warfare is not prohibited it cannot safely be said to be over. These changes, together with the marked emergence of the under-developed and former colonial peoples, indicate that

a new phase of the general transformation of society is definitely opening.

In tracing the interactions of science and society in detail it should be sufficient to have in mind the general character of the different periods, and to remember also that ever since 1917 two world economies have to be considered, and that since 1945 the peoples of Asia and of other undeveloped countries are coming into the picture.

In the following four chapters the progress of the physical, of the biological, and of the social sciences are successively traced. The treatment is necessarily different in each case. The physical sciences, which are discussed in Chapter 10, underwent in the twentieth century a revolution as important and far more rapid than the great seventeenth-century revolution. It was one which enormously increased their power as a means of understanding not only physics and chemistry but every branch of science. Biology, on the other hand, as will be shown in Chapter 11, was almost as radically transformed, but this was marked rather by a proliferating expansion than by any sharp break. The influences came largely from outside in the form of new techniques, new ideas, and new explanations from other sciences under the pressure of new problems presented by an expanding agriculture and medicine.

The situation of the social sciences is in a different category again. In the natural sciences the problem facing us in this book is to bring out social and economic factors and resultants from a body of knowledge which reflects a Nature largely independent of human society. In the social sciences, on the other hand, where what is reflected is human society itself, the problem is to disentangle any objective reality from a maze of venerable traditions and new theories which consciously or unconsciously serve to perpetuate the rule of the wealthy. For that reason the treatment of the social sciences here has to be a much broader one, and must reach back much farther into past history. It cannot be confined, as are those dealing with the physical and biological sciences, to the twentieth century. Accordingly it is dealt with in two further chapters. The first of these, 12, treats of the general nature of the social sciences and their history before the twentieth century; the second, 13, brings the story up to date.

Professor Bernal's great book has the dynamics by which man's social relationships, institutions, and culture acted now as creators, and now as deterrents, to this massive and glorious forward sweep of science.

J. D. Bernal holds the unique position of being one of, if not *the*, leading scientific mind of Great Britain, and, at the same time, is a socialist, not of the British Labour Party, but of the Marxist persuasion. His vast energy has enabled him to be an innovator in his own field (the structure of matter), a sociologist and historian of science, and an active participant in the politics of his time. His book, *The Social Function Of Science*, is itself a milestone in the sociology of science; *The Freedom Of Necessity* is a notable contribution to the philosophy of our times; *The Physical Basis Of Life* is a bold probe into the theory of the very origin of life.

SCIENCE IN HISTORY by J. D. Bernal

Science In History is his major work to date—a brilliant and sweeping view of the history of science and a most penetrating and thought-provoking study of the relationship of science to the society and history of mankind. But Professor Bernal is not interested only in the fascinating history of science as such. As the conservative English journal, *Economist*, put it "Judged purely as a history of science, this must be considered exceptionally good . . . the author has an attractive pithy style and writes clearly in the popular language. . . . But this is much more than a mere history of science, and the author's grasp of the complex interactions of science with history is even more remarkable."

Bernal believes that the "troubles of our times," as he, himself, puts it in the preface of *Science In History*, "together with the inescapable connections between them and the recent exposure to the advance of science, have focussed attention on the historical aspect of science. To find how to overcome the difficulties that face us and to release the new forces of science for welfare rather than destruction, it is necessary to examine anew how the present situation came about." *Science In History* pursues the fabulous achievements of science from prehistoric times, when the first effort was made by man to control his environment, to atomic energy, man-made moons, and the computer-automation technique of our times, but it does it with this prime purpose in mind: *What is the relationship between the way man lives, makes his living, organizes his economy and his society, on the one hand, and the growth and achievement of science on the other?*

Although a great scientist himself, Professor Bernal has approached this wonderful and dangerous subject as both scientist *and citizen.* The reader of this book will see the emergence of the intricate threads of science, follow the work of known and unknown innovators, the heroes of science; but his eyes and mind will be focussed the while on the sociology of science. How did the discovery of fire and the ability to chip flint change the world of prehistoric man; how did the discovery of metal smelting change man's culture; what were the scientific and social consequences of Lavoisier's discovery of the Periodic Table; what was the meaning of the Newtonian synthesis, of Einstein's theories, of Heisenberg's uncertainty principle? For the first time science is seen not in the light of "Gee, aint it wonderful how they do it?" but in the light of "How, really, does it change our lives and how can we master it?"

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